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DESIGN AND MANAGEMENT OF SUBSURFACE SOIL ABSORPTION SYSTEMS

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16. ABSTRACT

The results of two studies are reported: (1) the effects of construction practices upon soil hydraulic properties; and (2) field examination of the effects of operational strategies upon soil infiltration properties.

The investigation of construction practices showed that heavy machinery traffic significantly reduces the porosity and infiltration rate of the bed. The degree of damage varies with soil texture, structure, and moisture content. Field trials demonstrated that a damaged absorption bed can be restored by removal of the compacted and sheared layers.

The investigation of operational strategies consisted of three application methods, each employing three loading rates. Soils with similar hydraulic properties and segregated and combined wastewaters from typical rural single-family homes were used.

Results of the first year of operation showed that soil infiltration rates decreased significantly for all loading methods and rates, suggesting progressive development of a biological clogging layer that impedes flow. Infiltration rates decreased most strongly for the conventional treatments, with the greatest decrease for the cells with higher loading rates. The analysis of results from once-daily-uniform versus conventional application implies that larger, less-frequent doses of septic tank effluent are superior to conventional application in order to maintain adequate absorption.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nations's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link betrween the researcher and the user community.

This study endeavored to determine several factors heretofore unquantified with regard to improved design and construction of subsurface soil absorption systems. Among these are the effects of dosing wastewater uniformly as compared to conventional gravity loading and quantifiable measurement of the effects of different construction practices on soil infiltration capacity. These efforts seek ultimately to improve the performance of subsurface soil absorption systems for the nearly thirty percent of the U.S. population which is not served by conventional sewerage, thereby saving several million dollars unnecessarily required to sewer this segment of the population.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

This report presents the results of continuing research regarding onsite wastewater disposal by the Small Scale Waste Management Project (SSWMP) at the University of Wisconsin-Madison. Reported here are the results of two separate investigations: (1) a study of the effects of soil absorption system construction practices upon soil hydraulic properties; and (2) a field examination of the effects of various operational strategies for soil absorption systems upon soil infiltration properties.

The investigation of construction practices showed that construction machinery traffic can significantly reduce the porosity and infiltration rate of a soil absorption bed. The degree of damage varies with soil texture, structure, and moisture content; wet soils are particularly vulnerable. Field trials demonstrated that a damaged absorption bed can be restored by removal of the compacted and sheared layers. Damage is best prevented, however, by preventing unnecessary compacting of the absorption bed area, especially that of construction machinery traffic.

The investigation of operational strategies for soil absorption systems consisted of three separate experiments: (1) comparison of conventional (simulated trickle) application of septic tank effluent to once-daily-uniform application; (2) alternating periods of effluent loading and resting compared to continuous conventional application; and (3) in-house segregation of greywater with the comparative application of greywater, combined wastewater, and a tapwater control. The experimental design of all three experiments employed three effluent loading rates, including the basic design loading rate of 2 cm/day, as well as 4 cm/day and 8 cm/day. The three experiments, implemented on soils with similar hydraulic properties and using wastewaters from typical rural single-family homes, employed soil absorption cells _in situ_ to simulate the conventional application of effluent. At each site, three replica cells for each treatment were constructed.

During the first year of operation of the conventional versus once-daily-uniform experiment, soil infiltration rates decreased significantly for all treatments and loading rates, suggesting the progressive development of a biological clogging layer that impedes flow.

In addition, infiltration rate has decreased most strongly for the conventional treatments, with the greatest decrease for the cells with higher loading rates. All once-daily-uniform treatments, regardless of loading rate, show higher infiltration rates than the conventional treatments. These preliminary results imply that larger, less-frequent doses of septic tank effluent are superior to conventional (trickle) application, to maintain hydraulic properties that allow adequate absorption.

This report was submitted in fulfillment of Grant No. R805531 by the University of Wisconsin under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period of November 1, 1977 to December 30, 1979, and the work is continuing.

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LIST OF ABBREVIATIONS AND SYMBOLS

B.D.	- bulk density
BOD5	- five-day biochemical oxygen demand
cc	- cubic centimeter
C.I.	- confidence interval
cap,c	- capita
cm	- centimeter
COD	- chemical oxygen demand
Coli	- coliform organisms
cu ft	- cubic feet
CV	- coefficient of variation
d	- day
D.O.	- dissolved oxygen
ES	- effective size
FC	- fecal coliform
FS	- fecal streptococcus
ft	- feet
ft^2	- square feet
g	- gram, gravitational constant
G	- geometric mean
gal	- gallon
gpd	- gallons per day
gpm	- gallons per minute
h, hr	- hour
H	- hydraulic head
Ho	- positive hydraulic head
ΔH	- change in hydraulic head
hp	- horsepower
i.d.	- inside diameter
in	- inch
JTU	- Jackson Turbidity Unit
Kg	- kilogram
KW	- kilowatt
KWhr	- kilowatt-hour
L	- liter, distance
lb	- pound
Log	- logarithm
Lpm	- liters per minute
m	- meter
m^2	- square meter
m^3	- cubic meter
mbar	- millibar
mm	- millimeter
MBAS	- Methylene Blue Active Substance
mg	- milligram
mg/L	- milligrams per liter
min	- minute
mL	- milliliter
MLSS	- mixed liquor suspended solids
MPN	- most probable number
M_s	- oven dry weight of soil
mv	- millivolt
M_w	- mass of water
N	- nitrogen, normal concentration, number
nm	- nanometer
o.d.	- outside diameter
ORP, Eh	- Oxidation-Reduction Potential
P	- phosphorus
p	- pressure
pH	- negative log of the hydrogen ion activity
PT	- ponding time
r	- radius
s	- submergence potential
SD, S_L	- standard deviation
STE	- septic tank effluent
SVI	- sludge volume index
t	- time
TBC	- total bacterial count
TC	- total coliforms
temp	- temperature
TS	- total solids
TSS	- total suspended solids
TVS	- total volatile solids

ABBREVIATIONS (cont.)

TVSS - total volatile suspended solids
UC - uniformity coefficient
V_a - volume of soil air
V_s - volume of solids
W - watt

SYMBOLS

^{o}C - degrees Celsius
$\nabla\phi$ - hydraulic gradient
ε - water-filled porosity
δ - specific weight
K - hydraulic conductivity
K_b - hydraulic conductivity of a crust or barrier
K_p - hydraulic conductivity after ponding occurs
K_s - hydraulic conductivity of of a soil under a crust or barrier
K_{sat} - saturated hydraulic conductivity
M - molar concentration
μ - micro, micron
μL - microliter
μM - micromoles
μm - micrometer
η - viscosity
- number
% - percentage
ψ_c - critical moisture potential
ψ_g - gravitational potential
ψ_m - matric or capillary potential
$\psi\Omega$ - overburden potential
ψ_o - osmotic potential
ψ_p - pressure potential
ψ_t - total potential of water
Q - flow rate
q_b - flux through crust or barrier
q_s - flux through soil
$\vec{q}$ - vector specific discharge
R_b - hydraulic resistance of barrier or crust
ρ_w - density of water
θ - volumetric moisture content
θ_v - percent soil moisture by volume
θ_w - percent soil moisture by weight
V - flux
V^1 - average velocity
Z - height above datum

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SECTION 1

INTRODUCTION

In 1970, approximately 19.5 million households or nearly 30% of the housing units in the USA disposed of their wastewater by some form of private sewerage facility (U.S. 1970 Census). Subsurface soil disposal of wastewater is the most common method employed. It was estimated that in 1971, 13 million private septic tank-soil absorption systems were in use in the USA serving over 50 million people (Patterson et al., 1971). The use of these systems has been increasing at a rate of about one-half million new systems per year. As populations begin to shift back to rural areas following industrial growth on the fringes of metropolitan centers or in retirement, the demand for on-site disposal systems will increase at an even higher rate.

What is most alarming is that subsurface wastewater disposal technology has continued to lag behind this new demand for effective systems. A large number of people today in rural areas lack satisfactory waste disposal facilities. In 1973, it was estimated that about five to ten million households use privies or directly discharge their untreated wastewater (Patterson et al., 1971). In addition, many septic tank systems are malfunctioning due to inappropriate design, construction and maintenance.

On-going research at the University of Wisconsin has provided a clearer understanding of the behavior of soils receiving wastewater effluents. This research has served as a basis for the development of procedures for soil absorption field design, construction and operation (Small Scale Waste Management Project, 1978). Numerous questions remained unanswered, however. Methods of modified conventional soil field operation and management, based upon hypotheses developed from previous soil studies, needed to be evaluated in a field program. In addition, an evaluation of construction practices as they influence soil absorption field performance was deemed necessary. Finally, an assessment was needed to identify the potential impacts of in-house segregation (i.e., the use of non-water carriage toilets) as related to the soil absorption of the remaining wastewater.

With the support of the U.S. Environmental Protection Agency (Grant No. R805531-01) and the State of Wisconsin, the Small Scale Waste Management Project (SSWMP) on-going at the University of Wisconsin-Madison has undertaken an investigation to accomplish the following objectives:

1. Evaluate the influence of present soil absorption area construction practices on soil infiltration characteristics and identify restoration methods for smeared or compacted soil;

2. Evaluate the effect of three, modified soil absorption field operation strategies on soil infiltration characteristics. The following modified strategies were selected for study:

   ——Once daily uniform application compared to conventional gravity application,

   ——Alternating periods of loading and resting compared to conventional continuous operation,

   ——In-house waste segregation with greywater application compared to conventional total wastewater application.

This report presents the interim results of this research effort. The first objective has been achieved and results of this phase of the study appear in Section 5. The remaining project objectives have not yet been completed. A progress report on these studies is presented in Section 6.

SECTION 2

CONCLUSIONS

SOIL ABSORPTION SYSTEM CONSTRUCTION

From a review of the pertinent literature the following conclusions are presented about construction of soil absorption areas (Section 5):

1. The effect of gravel dumping on the infiltrative capacity of a soil absorption system has not been quantified.
2. No chemical stabilization agents are capable of increasing soil strength enough to prevent damage during construction of soil absorption systems.
3. Work should be scheduled to avoid rainfall onto the soil infiltrative surface.

Based on the results of the field trials the following conclusions are presented about construction of soil absorption areas.

1. Machine excavation produced smeared surfaces which were clearly visible.
2. The type of bucket used had a pronounced effect on observable smearing. A smooth-edged bucket created a smeared surface of two to six centimeter wide plates over the whole bed. The tooth-edged bucket left smear marks only where the teeth came in contact with the soil.
3. In the smooth, slick areas left by both types of backhoe buckets the number of large pores was reduced. The pores that remained in these areas tended to be aligned horizontally.
4. The soil in the bed which was excavated with the smooth-edged bucket had a reduced infiltration rate.

5. Infiltration rates in the beds which were excavated with a tooth-edged bucket varied greatly.

6. In the moist soil trials wheel traffic produced smooth and slick tracks with machine-induced platy structure. Wheel traffic produced smooth tracks in the dry Plano soil trial. No smooth or slick tracks were found in the dry Ontonagon soil.

7. Porosity decreased in all trials except in the case of the dry Ontonagon soil in which case it increased. The reduction in porosity was the most severe in the moist soil trials and was greater with increasing traffic. Porosity decreased in the larger pore sizes and increased slightly with compaction in the smallest pore sizes.

8. The pores that remained after compaction were oriented horizontally.

9. Wheel traffic reduced infiltration rates in all cases except the trial with the dry Ontonagon soil. In the trials where the infiltration rate was reduced an increase in the amount of traffic corresponded with greater decreases in the soil's infiltration rate.

10. Removal of the disturbed surface resulted in infiltration rates returning to approximately the same rate as for undisturbed soil. Depth of removal necessary to return to the undisturbed infiltration rate increased with increased wheel traffic.

11. The weaker soil structure in the dry Plano soil resulted in its being crushed more readily by machinery than the more strongly structured dry Ontonagon soil.

12. The hand penetrometer used was able to determine soil strength as affected by moisture content. It was not able to consistently determine the varying degrees of compaction produced by different amounts of machinery traffic.

Modified Soil Absorption Systems

Based on the experience to date with the modified absorption system experiments (Section 6), particularly the extended period of operation at Site 1, the following conclusions can be advanced with regard to alternative management strategies for on-site systems. Because of the current on-going status of these experiments, results and conclusions presented here should be regarded as preliminary. Only continued intensive monitoring of these experiments by the methods described in this report, as well as newly refined and applied techniques, can provide the information sought in the original project objectives.

1. All experimental cells appear to be developing biological clogging layers with cumulative effluent application, but at varying rates.

2. In all cells, infiltration rates are declining significantly with cumulative effluent application.

3. Decline of infiltration rate (or effluent absorption capacity) is very strongly linked to the frequency and amounts of effluent application.

    (a) Conventional (simulated trickle) application of effluent causes a faster and more complete decline in infiltration rate than effluent applied in a once-daily dose.

    (b) Increasing the daily effluent loading rate in conventional systems contributes to the steady decline of infiltration rate over the life of the system.

    (c) Increasing the effluent loading rate in systems using the once-daily dosing method does not yet appear to strongly affect infiltration rate over time.

4. Observations of soil moisture tension support the concept of progressive biological crust development at the cell's soil infiltrative surface.

5. The frequency and depth of intermittent and persistent ponding above the infiltrative surface implies the development of crusts which impede the absorption of effluent. These measurements suggest that the conventional (simulated trickle) application method, particularly at high effluent loading rates, are progressing toward eventual hydraulic failure.

6. All soil moisture measurements attempted thus far in these experiments have demonstrated the dynamic nature of the systems under study. Only through extended intensive monitoring and innovative research can an understanding of the many interacting mechanisms be developed.

7. Findings to date suggest that once-daily dosing of the effluent load appears to be superior to the conventional trickle application approach in terms of maintaining hydraulic properties of the soil system. However, this project has thus far considered only the hydraulic loading concern, and has not addressed the issue of whether increased hydraulic loading of effluent by dosing and higher application rates assures an acceptable level of effluent treatment.

8. Application of both greywater and total waste to two parallel soil absorption fields in a silt loam soil is underway, but it is premature to draw any conclusions at this time regarding the relative rates of clogging of these two systems.

SECTION 3

RECOMMENDATIONS

SOIL ABSORPTION SYSTEM CONSTRUCTION

1. More research is needed on the effect of gravel dumping on the infiltrative capacity of soil absorption systems.
2. Additional research is needed to quantify the effect of various backhoe bucket types on soil infiltration rates.
3. Based on the conclusions the following recommendations are made:
    - A. All traffic should be kept out of the bed;
    - B. A tooth-edged backhoe bucket should be used for soil absorption system construction;
    - C. Work should only be done when the soil is dry.

MODIFIED SOIL ABSORPTION SYSTEMS

1. Continued research of modified soil absorption systems is needed.

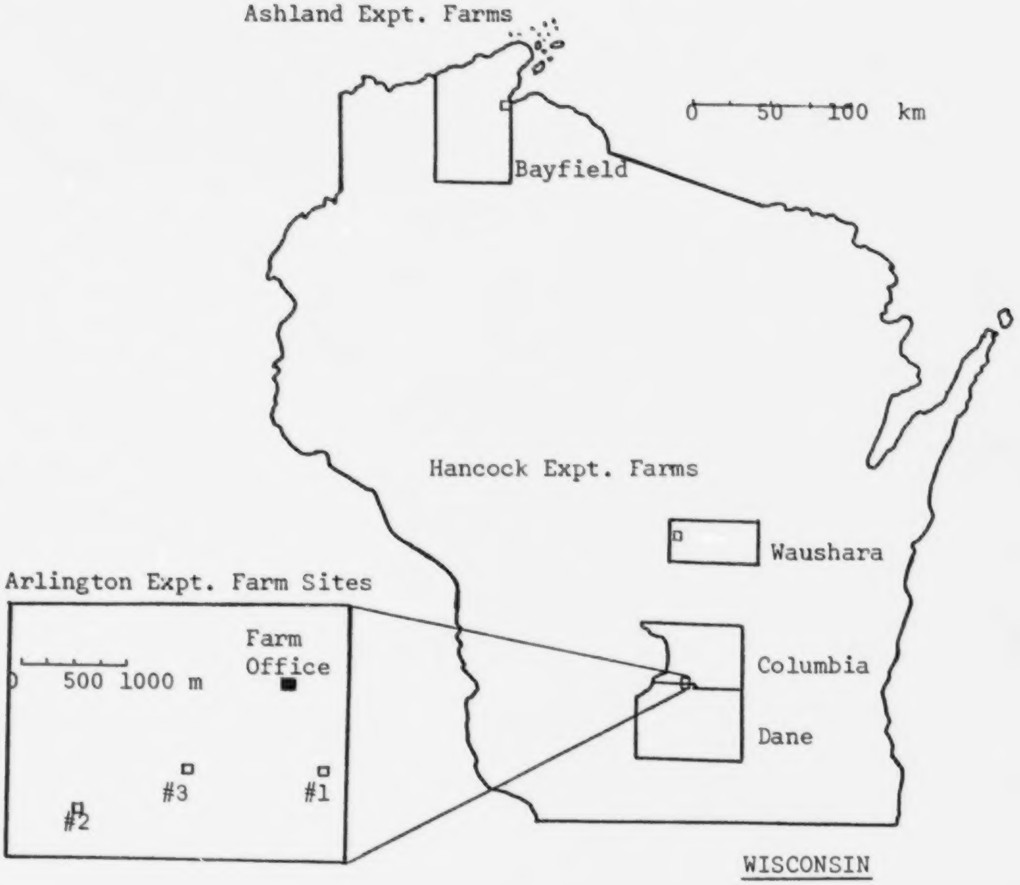
SECTION 4

FIELD STUDY AREAS

STUDY OF MODIFIED SOIL ABSORPTION SYSTEMS

The field study of experimental soil absorption systems took place at University of Wisconsin facilities at Arlington Experimental Farms, approximately 23 kilometers north of Madison (Fig. 4-1). The Arlington farms are located near the town of Arlington with lands in Dane and Columbia counties. Each of the three experimental systems at Arlington was adjacent to a farm residence, the home of farm employees. The three sites were approximately 2 kilometers apart and all within a 3-kilometer radius of the experimental farms' office. Figure 4-2 depicts the location of the respective sites, the farm offices, and the general character of the local landscape. The three sites used in the study of experimental soil absorption systems were selected based on several factors. Soil conditions were nearly uniform between the three sites and suitable for installation of conventional soil absorption systems. Also, the wastewater production characteristics of the homes were appropriate for study needs.

Objectives of the study required that soil conditions on the three soil absorption system sites be as similar as possible. All three sites occupied similar positions on the gently rolling, loess-covered ground moraine landscape. The soils at each site were the Plano silt loam, a well-drained member of the fine-silty, mixed, mesic, Typic Argiudolls. One of the three sites is in a mapping unit of Ringwood silt loam that is classified similarly to Plano, except that it is a member of the fine-loamy family (Soil Conservation Service, 1978b). Careful examination of the soil profile at the study site showed the materials to fall within the range of characteristics of Plano silt loam (Soil Conservation Service, 1973a; 1978a,b). Mapping units of Plano and Ringwood commonly intergrade and have inclusions of one another. As indicated by the taxonomic similarities of these series, the interpretive properties for the purpose of soil absorption systems are almost identical (Soil Conservation Service, 1967; Soil Survey Staff, 1978a,b).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Hancock Expt. Farms
Waushara
Arlington Expt. Farm Sites
Farm Office
0 500 1000 m
#3
#1
#2
Columbia
Dane
WISCONSIN

Figure 4-1. Location of field study and sampling sites.

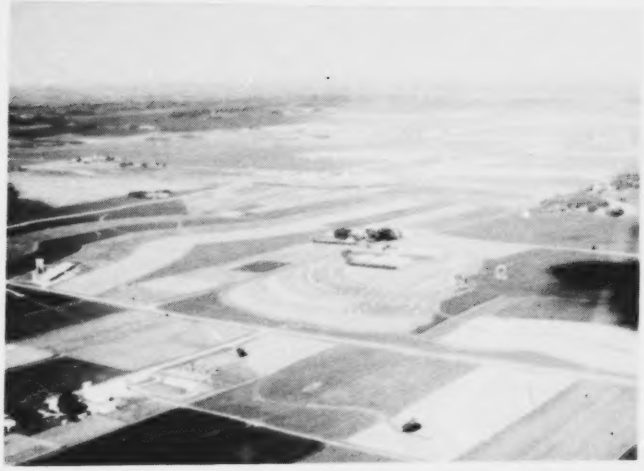

Figure 4-2. Airphoto of the Arlington sites, looking to northeast.

The bedrock underlying the Arlington sites is dominated by Prairie du Chien dolomite of Ordovician age (Martin, 1967). Overlying the dolomite is a sandy loam till covered with 1 to 1.5 meters of wind-blown silt from which Plano and related soils have developed. These sites are in the Yahara River watershed which drains into Lake Mendota.

The Plano soils at Arlington have developed beneath native tall grass prairie, as evidenced by their thick, dark silt loam surface horizon. Land use at all three sites has been either pasture, row crops, or residential lawn for at least 80 years. The Arlington sites are in the humid, continental climate zone, with warm summers and long, cold winters. There is an average of 176 frost-free days per year at Arlington. Each site was almost level to gently sloping (1 to 5%). Site 1 had a slight northwesterly aspect. Sites 2 and 3 had southwesterly and northerly aspects, respectively.

STUDY OF CONSTRUCTION PRACTICES

The influence of construction practices upon selected soil properties was studied at two field locations. Site 2, Arlington Experimental Farms, as previously described, was the site of three construction experiments. The excavated area was located within a 75-meter radius of the soil absorption system experiments at this site.

The other two experiments of the construction phase of the study were conducted at the University of Wisconsin facilities at Ashland Experimental Farms, near Ashland, Wisconsin. This site is approximately 480 kilometers north of Madison, just 3 kilometers from Lake Superior, in Bayfield County (Fig. 4-1).

The Ashland site was selected because it had distinctively different soil conditions from those found at Arlington. The soil at the Ashland site is Ontonagon silty clay loam, a moderately-well drained member of the very fine, illitic, Typic Eutroboralfs (Soil Survey Staff, 1970). The immediate site area has since been maintained in row crops, pasture, or residential lawn.

Ontonagon has developed in calcareous glacio-lacustrine clay sediments that are underlain by glacial drift over Precambrian upper-Keweenawan non-calcareous sedimentary rocks (Martin, 1965).

The Ontonagon soils at Ashland were covered by native boreal forest until approximately 80 years ago. Ashland is in the humid, continental climate zone, with warm,humid summers and long, cold winters. There is an average of 118 frost-free days per year at Ashland. The site is almost level, with a slope of less than 2% and a northerly aspect.

SECTION 5

EFFECTS OF CONSTRUCTION PRACTICES ON SOIL ABSORPTION AREAS FOR WASTEWATER DISPOSAL

LITERATURE REVIEW

Introduction

Septic tank-soil absorption field wastewater disposal systems serve about one quarter of U.S. households, mostly in rural and suburban areas (Cooper and Rezek, 1977; Otis et al., 1977). Failures of these systems have frequently been traced to system installation in soils with inadequate natural drainage or hydraulic conductivity (permeability). Better site selection and system design criteria are reducing the frequency of these failures (Small Scale Waste Management Project, 1978), but additional factors seem to be involved in many cases of failure.

Some workers have suggested that alteration of soil structure by construction machinery during system installation may be a major cause of system failures on otherwise suitable sites, particularly those failures that occur during the first year of system operation. However, the link between construction compaction and system failure has not been documented. Cautions and recommendations for system construction have been published (Otis et al., 1977; Small Scale Waste Management Project, 1978), but lack substantiating evidence. Bouma (1975a) also suggests ways to avoid compaction and smearing during system construction, supported by sketchy data in the form of "approximate" infiltration rates for "uncrusted" and "puddled" soils of sandy loam, silt loam, and clay texture. Infiltration rates for the "puddled" soils were 10 to 100 times slower than for "uncrusted" soils. However, the experimental procedure is not detailed. There is no indication of how the puddled soils were prepared, nor whether the degree of compaction of these puddled soils is comparable to that resulting from soil absorption system construction. Indeed, there is no assurance that all these figures are based on experimental results.

No published study of the effect of soil absorption system construction practices on soil hydraulic properties has been found. To fill that gap, this review relates the literature in soil science to that of civil and agricultural engineering, and predicts how soil hydraulic properties may be affected by absorption system construction.

The Soil-Water System[1]

The Soil System--

Three-phase systems--Soils are three-phase systems composed of solid mineral or organic particles, liquids (mostly water) and gases. The liquid and gas phases are present in the pores between the solid particles. The hydraulic properties of the soil are controlled by these pores, and changes in these properties result when the pore system is altered by the movement or displacement of solid particles. Because of the nature of the pore system of soil, changes in soil water content also strongly affect soil hydraulic behavior.

Individual mineral[2] soil particles tend to be round or irregularly shaped in the larger size fractions (sand and silt), while the smaller particles (clay-size) are generally platy in shape. The rearrangement of these particles may reduce hydraulic conductivity by creating barriers to flow, especially when platy clay particles are moved into a parallel orientation (Fig. 5-1).

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[1] Material in this section can be found in Baver et al. (1972), Foth (1978), and similar texts in introductory soil science and soil physics. Additional references are cited where appropriate.

[2] Organic soils are not considered in this review, and the organic components of mineral soils are assumed to possess properties similar to clay mineral particles, though organic components can significantly alter soil hydraulic behavior (Harter, 1977).

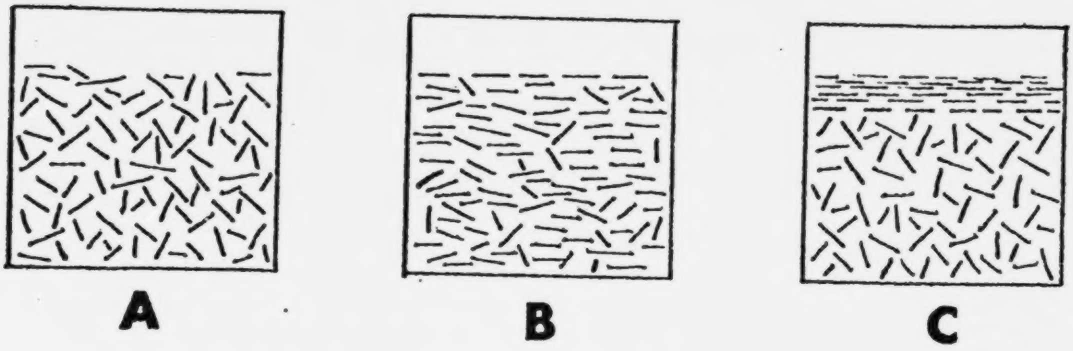

Figure 5-1. Idealized clay particle orientation (A) in natural soil; (B) after exposure to compressive forces; (C) after exposure to shearing forces. Adapted from Seed (undated).

Soil texture is the relative proportion of the three particle size separates -- sand, silt, and clay. Texture is probably the most important single attribute of a soil, as it has profound effects upon most other soil properties, particularly hydraulic properties. In general, coarse-textured (sandy) soils exhibit much higher saturated hydraulic conductivities than fine-textured (clayey) soils, but during highly unsaturated flow, this order is reversed.

Soil structure is the physical arrangement of individual solid particles. Most soils exhibit aggregation -- the clumping of groups of particles into more or less stable units called peds. Large voids within these peds, and especially the spaces between peds, are the principal pathways of saturated flow in structured soils. In soils with significant quantities of certain clay minerals, soil swelling may squeeze and close off these pathways, drastically reducing hydraulic conductivity.

Soil porosity is the percentage of the whole soil mass which is not occupied by solids, and can be derived from bulk density data, provided that the average specific gravity of the solid particles is known. However, a more useful parameter is the frequency distribution of different pore sizes in the soil, since under even slightly unsaturated conditions, large size pores will not conduct water. Soils of equal total porosity can have very different hydraulic characteristics depending upon their pore size distributions.

The soil profile--A soil profile is a sequence of layers or soil horizons. The properties of a soil's horizons may differ because of differences in the soil's initial materials, or as a result of changes produced by soil-forming processes. Surface horizons are typically zones of accumulation of organic matter. In the well-drained soils that are commonly considered for disposal of on-site wastes, the subsoil horizons are typically enriched in clay-size particles and iron and aluminum oxides, leached from overlying horizons by percolating waters. Below the subsoil (and usually within 2 meters of the surface in the temperate region) is found geologic material relatively unaltered by the processes that formed the soil above. This may be consolidated or unconsolidated material, and may or may not be similar to the initial material in which the overlying soil formed.

Soil Water--

The term "soil moisture potential" refers to the energy status of soil water. All water movement in soils occurs in response to potential gradients. While saturated flow is fairly straightforward, unsaturated flow of soil water can be predicted only after understanding the moisture potential concept.

The types of moisture potential that are important to an understanding of long-term flow patterns under soil absorption systems are gravitational potential, matric potential, and to some extent, pressure potential.[3] The potential possessed by a volume of water solely by virtue of its elevation above or below a reference elevation or datum is gravitational potential. Water above a given datum has a higher gravitational potential than water at or below that datum.

Matric potential results from the tendency of water molecules to adhere to solid surfaces, and to cohere to each other. Matric potentials are either negative in value or zero. Since the surface area/volume ratio of small vessels is much larger than that of large vessels, a unit volume of water in small-diameter pores is in contact with more solid surface than a unit volume of water held in large-diameter pores. Hence, water in finely-porous soil is more tightly held than water in coarsely-porous soil. Because of this stronger holding or pulling power, fine pores can become or remain water-filled at much lower moisture potentials (higher suctions) than can large pores.

Positive pressure potentials are found below the free water surface of water tables or other ponded water, and result from the weight of overlying free water.[4] By definition, matric and pressure potentials are opposite in sign, and at any point, if one is non-zero, the other must be zero.

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[3] Osmotic potential may be of importance when considering effects on soil swelling of high salt concentrations in soil or applied wastewater, but typically has a negligible intrinsic effect on unsaturated flow under soil absorption systems.

[4] Pressure potentials may also result from gas pressures higher than atmospheric pressure, but this is seldom encountered.

Soil Water Movement--

All soil water movement occurs in response to potential gradients, from regions of high potential to regions of low potential. This relation is easy to apply in uniform porous media, but becomes more complex in non-uniform cases, as in layered soils.

Saturated flow--The rate of saturated flow in soils depends upon the total amount of porosity and the size of the individual pores. Large diameter pores with a given total cross-sectional area will conduct water much more rapidly than the same cross-sectional area of small diameter pores, since flow velocity is proportional to the square of the radius of the conducting vessel. Thus, sandy soils, with their large size pores, exhibit much higher saturated conductivity values than finely-porous clayey soils, even though the total porosity of clayey soils is usually greater than that of sandy soils.

In soils formed in relatively uniform unconsolidated material, the saturated hydraulic conductivity of the surface horizon is often enhanced by the loose, porous structure of stable granular aggregates bound by organic matter. Saturated hydraulic conductivity is usually slower in the subsoil horizons, due to the reduced porosities and smaller pore sizes of these clayier horizons. In soil developed in clayey materials, the subsoil may initially exhibit a more rapid saturated hydraulic conductivity than would the initial material, due to an extensive network of cracks between structural units, but under long-term near-saturation conditions, as under a soil absorption system, these cracks are apt to remain closed if substantial amounts of swelling-type clays are present. Clayey subsoil horizons with large numbers of long tubular biopores (e.g., earthworm channels) may continue to exhibit saturated hydraulic conductivity rates much faster than would be predicted on the basis of texture alone.

The saturated hydraulic conductivity of soils developed in deep, uniform, unconsolidated materials typically follows a pattern with depth, from relatively rapid to slow to moderate. Soil absorption systems to be installed in subsoil horizons of such soils usually must be designed more conservatively than those to be placed in the underlying initial material.

Unsaturated flow--Sandy soils exhibit much faster saturated flow than do clayey soils; however, as moisture content decreases, this trend is reversed. At high soil moisture tensions (low moisture potentials), very few pores in a sandy soil can exert enough "pull" to remain filled with water, while many of the pores in a clayey soil are fine enough to remain water-filled. At these tensions, clayey soils will conduct water more rapidly than sandy soils.

In layered soils, a wetting front will move from a coarse-textured layer into a fine-textured layer, because fine pores pull water from the larger pores of the coarse material. However, the rate of water movement will be slowed, due to the pore size-velocity relations already discussed. When a wetting front advances through a fine-textured material toward a coarse-textured layer, that front will stop at the interface, because the water does not have sufficient energy to overcome the capillary tension exerted by the fine pores. The front will not move until enough water accumulates behind it; this raises the moisture potential high enough for the large pores of the coarse-textured layer to be able to pull water from the finer layer. If water is entering sand from a fine layer, the fine layer must become nearly saturated just above the interface before the sand will conduct water.

Effects of compaction or smearing--As we consider machine compaction of soil material, we would expect the same principles of water movement to apply. By sealing off large pores, cracks and channels, even a thinly-smeared layer on an infiltrative surface will seriously impair infiltrative ability. Surface seals resulting from raindrop impact may also seriously reduce infiltration.

Compaction or compression, as under a static load, reduces saturated hydraulic conductivity by squeezing large pores, thus leaving smaller pores. Although compaction reduces macroporosity, it generally increases microporosity (Foth, 1978). Thus, compaction would reduce saturated hydraulic conductivity, but could actually increase hydraulic conductivity in a portion of the unsaturated range; that is, in a relatively dry soil.

Absorption System Construction

Current Construction Practices--

Although there appears to be an increasing trend toward using large, long-reach machines for absorption system excavation, most such excavation seems to be done with small- to medium-sized, backhoe-equipped tractors, which frequently also have front-end loaders. The backhoe typically excavates a rectangular bed, with the machine itself usually remaining outside the excavation. However, when working areas are confined, or when small, short-reach machines excavate large beds, deepening or leveling the excavation may force the operator to drive into the excavation.

Wheel traffic across the bed is precluded when rectangular bed areas are replaced by one or more narrow trenches which can be straddled by the excavating machine. Such trench methods of construction are being incorporated into state and local codes regulating absorption system installation (e.g., Bouma, 1975a; Wisconsin Division of Health, 1976).

After excavation, gravel is placed in the absorption bed. Typically this is done with a tractor-mounted front-end loader, though sometimes gravel is dumped directly from large trucks. The impact force of this falling gravel may itself disrupt soil structure.

Though gravel can be dumped fairly uniformly from the edge of a trench, gravel in larger excavations must be spread over the area. Although this can be done by hand, machines are usually used. Often, the machine remains outside the excavation, and the extended backhoe is used to spread and level the gravel. Some contractors then drive on top of the spread gravel and use the backhoe to excavate shallow (5 to 7 cm) trenches in the gravel in which the distribution pipe will be placed. Other installers use their front-end loaders as grading blades, driving into the excavation on a layer of gravel. A few carry this idea further by using a bulldozer for this grading. A thick layer of gravel will protect the infiltrative surface from damage due to wheel slip (Raghavan et al., 1978), and will spread vehicle weight over a larger area (Sowers and Sowers, 1970); however, it is not yet clear how thick this gravel layer must be, nor whether such protection will be adequate under all texture and moisture conditions.

Although many contractors avoid driving on unprotected infiltration surfaces, many others do, in fact, drive their machines into absorption system excavations to level uneven excavation work or to dump and then spread the gravel. Informal interviews with some absorption system installers suggest that in at least some cases of very early absorption system failure, wheel traffic on the excavated beds has been involved.

Effect of Forces on Soils--

Three types of forces could conceivably act on the soil when machinery is used to construct soil absorption systems. These are compressive, shearing and vibratory forces (Sowers and Sowers, 1970; Cohron, 1971).

Compressive forces--Compressive forces may act to a significant depth in soil, depending upon the load applied, the duration and frequency of load application and the size of the loaded area. In the wheel traffic case, compaction increases with repeated passes, but the amount of increase tapers off logarithmically. Up to an optimum compaction level, compaction also increases with water content, since the water reduces inter-particle

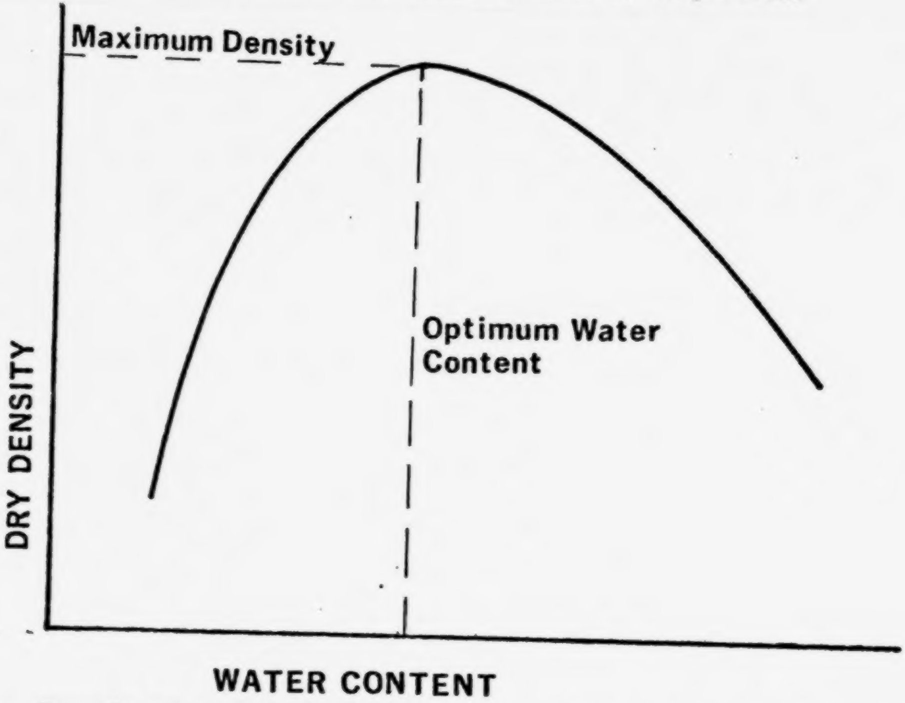

Figure 5-2. Example of a soil compaction curve. Adapted from Lambe (1958b).

friction. However, compaction actually decreases at higher water contents, since a larger and larger proportion of the pore space is occupied by incompressible water (Fig. 5-2). (These principles of compaction are summarized in Sowers and Sowers, 1970). Compressive forces may bring about changes in soil bulk density, pore size distribution and particle orientation. In clayey soils, the degree of particle re-orientation increases dramatically during compaction at moisture contents at and above an optimum level for compaction, while compaction at increasing water contents produces lower bulk densities (Seed, undated).

Thus, at low molding water contents in clayey soils, reduction in porosity is the principal soil response to compaction, while the dominant change at high molding water contents is the re-orientation of clay particles into a parallel configuration (Lambe, 1958a).

According to Lambe (1958b), hydraulic conductivity (permeability) is sharply reduced by compaction at increasing water contents, until a minimum is reached near the optimum moisture content for compaction, corresponding to maximum bulk density and minimum porosity. At increasing water contents, conductivity remains at or near its minimum value, even though porosity is much greater than minimum. The sustained low conductivity is due to the parallel orientation of particles in the compacted material. The higher porosity of the wet compacted soil is typically negated by the sealing action of parallel clay particles, reducing the degree of inter-connection of individual pores.

Compressional forces can produce dramatic changes in the distribution of various pore sizes in soils, particularly in silty and clayey soils. However, the data of Bodman and Constantin (1965) indicate that sandy soils are also significantly affected; in fact, compaction virtually eliminated large and medium size pores in mixtures of silty clay and fine sand, including up to 60% fine sand. Macroporosity reductions in sandier mixtures were smaller, but still noticeable. Further, intermediate mixtures, containing appreciable quantities of both fine sand and silty clay, exhibited lower total porosity when compacted than did mixtures containing mostly one texture or the other. These mixtures allowed small particles to fit into the voids between large grains, creating a dense matrix (Warkentin, 1971). In this particular experiment, the minimum compacted porosity occurred in a mixture of 80% sand and 20% silty clay. This corresponds to a texture in the loamy sand-sandy loam range.

Akram and Kemper (1979) found that the optimum water contents for compaction of five different soil textures under moderate loads fell very close to the field moisture capacity of each soil. At optimum moisture, loads reasonably similar to those that might be imposed by absorption system construction machinery reduced infiltration rates in sandy soil materials by 10- to 100-fold, and in clayey soil materials by 100- to 1000-fold. These data suggest that very severe infiltration reductions might occur when moist soil is driven on during absorption system construction. However, these experiments were not carried out on natural soils, but on soil materials which had been dried, broken, and sieved to eliminate aggregates larger than 7.6 mm. This study thus gives no clear indication of how natural soil structure in an absorption system excavation will react to wheel traffic and other construction practices.

Douglas and McKeyes (1978) examined the effect of compaction upon hydraulic conductivity at moisture potentials lower (drier) than saturation. Samples of a clay soil were compacted in the laboratory, then subjected to hydraulic conductivity measurements at moisture potentials ranging from 0 (saturation) to -5000 mbar. Unfortunately, the molding water content of the soil during compaction was not specified.

At compression levels commonly found under agricultural tillage equipment, as well as under equipment commonly employed in constructing on-site wastewater absorption systems, a reduction in subsequent hydraulic conductivity of the compacted soil seemed to occur in the range of 0 to 2 pF (1 to 100 mbar suction), which covers the range of moisture potentials commonly found under operating absorption systems (Small Scale Waste Management Project, 1978). However, this reduction was by no means uniform across the several levels of compactive effort. In several cases the compacted soil showed a faster unsaturated hydraulic conductivity than the loose soil. This may have been a real effect brought about by a shift of the pore size distribution, increasing the number of pores in the corresponding size range, or may simply have been due to experimental error.

Shearing forces--Shearing forces are those which cause one part of the mass acted upon to slip or slide relative to the remainder of that mass. Typical sources of shearing forces in soils are tillage implements and other cutting tools, such as backhoe and other buckets used in excavation. However, tillage tools also exert considerable compressive force on underlying soil (Cohron, 1971). This suggests that combinations of these different forces are involved in situations apparently controlled by just one force. Day and Holmgren (1952) found that volume changes in samples subjected to purely compressive forces were due in large part to plastic deformation of soil aggregates, involving shearing forces within individual aggregates. The highly parallel orientation of clay particles in soils that have been compacted when very wet probably reflects the increased incidence of shearing forces developed inside aggregates at these high water contents. This shearing-deformation action is most pronounced at moisture contents at and above the plastic limit of the soil, which likely approximates the water content for optimum compaction under the compression loads that might be expected during absorption system construction (Felt, 1965; Sowers and Sowers, 1970).[5]

Rubber-tired wheel traffic imposes a combination of compressive and shearing forces on soil. Contact pressures under rolling tires vary considerably across tire tracks (Cohron, 1971). These differential pressures produce differential movement of soil mass, and hence movement of one mass relative to another (shearing). Additionally, the flexing and stretching action of rolling tires can exert lateral shearing forces on the soil, producing a slick, smeared surface, especially at high soil moisture contents.

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[5] Under the substantially higher loads employed during the purposeful compaction stabilization of soil materials, the optimum moisture content is typically several percentage points drier than the plastic limit (Flet, 1965).

Much greater smearing can occur when wheels slip. Further, the degree of compaction (volume reduction) under tires is significantly increased by wheel slippage (Raghavan et al., 1978). For several tire sizes studied, compaction of a clay soil beneath a loaded tire was more than doubled by a 20% slippage of that tire. Maximum shearing appeared to occur at moisture contents wetter than the optimum moisture content for compaction. More severe wheel-slip effects were cited for sandy soils (Raghavan et al., 1977; Raghavan and McKeyes, 1977).

The distribution of contact pressures beneath rolling tires depends upon many factors, including soil texture, bulk density, moisture content, tire inflation pressure, sidewall stiffness, contact area, and vehicle weight (Cohron, 1971). In most cases, agricultural tire design has achieved a compromise that reduces overall compaction, confining it to a shallow enough depth for ordinary tillage tools to counteract. However, this approach may not be suitable for the construction of absorption fields, since subsequent tillage is typically not performed. Spreading vehicle weight over a larger tire contact area may simply increase the area adversely affected.

Little work appears to have been done relating hydraulic conductivity to shearing forces acting on soils. Ojeniyi and Dexter (1979) found that agricultural tillage resulted in the greatest destruction of soil structural aggregates and the smallest amount of soil macroporosity when the soil moisture content was at or slightly drier than the soil's plastic limit. These results are in substantial agreement with those of Allmaras et al. (1969). Typical agricultural tillage involves shearing forces acting on the soil (Cohron, 1971).

Vibratory forces--Vibratory forces are commonly employed in the densification of sandy soil materials (Sowers and Sowers, 1970), but the equipment and forces used are of much larger magnitude than those commonly at work during subsurface soil absorption system construction. Vibration has a lesser effect in clayey soils. Little work has been done to quantify the secondary effect of vibration on hydraulic conductivity, but this would seem to be minor in most cases of absorption system construction. A possible exception would be during the placement of sandy fill materials, as during the construction of mound systems. If the sand is clean and uniform, however, any densification caused by vibration may actually be beneficial, by preventing post-construction settlement. Machine vibration may play a significant role in destroying dry soil aggregates under wheel traffic, but it does not appear that this influence can be predicted for absorption area construction at this time.

Other Effects during Construction--

Raindrop impact--A number of researchers have examined the relationship between rainfall-induced surface crusting and infiltration. Such surface crusts often resemble the smeared surfaces produced by shearing forces. Both kinds of surfaces commonly exhibit high bulk densities and a high degree of parallel orientation of clay particles (Robertson and Erickson, 1978).

Surface crusts can significantly reduce infiltration. In results that seem to be fairly typical, Edwards and Larson (1969) attributed infiltration reductions of up to 50% to crusts induced by simulated rainfall on a silt loam soil. Such data stress the importance of protecting excavated absorption systems from raindrop impact, either by work scheduling or by physical protection.

The detrimental effects of raindrop impact may be even more significant when raindrops strike previously compacted surfaces. Hegarty and Royle. (1978) found that 1 mm or 5 mm of simulated rainfall greatly increased the penetration resistance of previously compacted samples. Although hydraulic conductivity was not measured, these data do suggest a significant densification of the samples, with a likely reduction in conductivity.

Protective Measures--

A number of chemical compounds have been tried as stabilizing agents for soils. These include polyvinyl alcohol (PVA), polyvinyl acetate (PVAc), polyacrylamide (PAM), bitumen or asphalt emulsions, and various non-ionic surfactants. None of these materials is capable of increasing soil strength enough to withstand construction compaction forces (Roose, 1975).

Non-ionic surfactants can increase infiltration rates when applied to hydrophobic soils, but have a negligible or negative effect on soil aggregate strength (Letey, 1975). Polyacrylamide, PVA, and PVAc can greatly increase the strength of soil aggregates against raindrop impact and reduce slaking, thus reducing surface crusting (Carr and Greenland, 1975; Dowdy, 1975; Gabriels and DeBoodt, 1975; Pla, 1975; Roose, 1975). Mausbach and Shrader (1975) tested PVA and PAM on silty and clayey subsoil materials, and found similar rainfall protection. By preventing crust formation, these chemical conditioners maintain high infiltration rates in soils subjected to rainfall.

Asphalt or bitumen emulsions are also effective soil stabilizers, and offer raindrop impact protection similar to that of PAM, PVA, and PVAc (Gabriels and DeBoodt, 1975; Pla, 1975). However, such emulsions are hydrophobic in nature, and thus tend to inhibit infiltration, though not to the same magnitude as would rainfall-induced crusting.

General costs for chemical treatment of soils appear to range from \$475 to \$4,750 per ha (Armbrust and Lyles, 1975). Based on a typical absorption system area of about 100 m^2 (Wisconsin Division of Health, 1976), these costs could range from about \$5 to about \$50 per system. Polyvinyl acetate applications studied by Roose (1975) cost about \$800 per ha, which would correspond to about \$8 per average absorption system. If further research can show any benefit from these materials in maintaining the infiltration rates of soil absorption systems, cost of material does not appear to be a major limiting factor.

Although these chemical conditioning agents might be of some use in protecting excavated subsurface absorption system areas from damage caused by raindrop impact, they are certainly not capable of withstanding wheel traffic or other major construction forces. Some chemical treatments might prove useful when systems are installed in naturally hydrophobic soil materials (e.g., non-ionic surfactants).

Restorative Techniques--

Methods of restoring compacted or smeared soil layers rely at least in part on some type of mechanical action. Agricultural tillage implements can be effective in breaking up compacted soils, though the tillage process itself subjects the soil to shearing and compressive forces (Cohron, 1971). Such tillage forces can result in the formation of smeared or compacted "plow soles" immediately beneath the depth of tillage (Baver et al., 1972). Thus, the use of such implements to break up compacted soils in absorption system excavations is not likely to result in a complete restoration of infiltrative capacity.

Another mechanical restoration technique is rototilling. Hoyle and Yamada (1975) found improved structure and increased aggregate stability in soils which had been rototilled while at a moisture of about 70% of field capacity. Although this method may produce ideal conditions in the seedbed, the degree of compaction or smearing immediately below the tillage depth is not indicated.

When unfavorable soil conditions are encountered during engineering projects, the most effective remedial technique is often removal and/or replacement of the undesirable soil material (Sowers and Sowers, 1970). This approach seems to offer promise in restoring infiltrative capacity when absorption system construction compaction has occurred. Since a backhoe was likely used to excavate the absorption area, no additional equipment must be obtained. Further wheel or foot traffic which would be imposed by tillage treatments can be avoided. Also, soil removal can be effective to a greater depth than some kinds of tillage (e.g., rototilling). This is important because compaction effects can extend beyond 30 cm depth (Cohron, 1971). The removed soil can be replaced by additional gravel, or the entire tile system may be lowered.

MATERIALS AND METHODS

Experimental Design

Two soils of different textures were selected for field trials. The Plano silt loam, a fine-silty, mixed, mesic Typic Argiudoll, was chosen to represent soils covering large areas of southern and western Wisconsin. These soils, although suited for soil absorption systems, have enough clay to make them susceptible to damage during construction (Bouma,1975a; Small Scale Waste Management Project, 1978).

The Ontonagon silty clay loam, a very fine, mixed Glossic Eutroboralf, had a clayey texture and represents soils occurring over much of eastern Wisconsin and some areas of the northern and north-central parts of the state. These soils are at best marginal in their suitability for subsurface soil absorption systems, and their high clay contents make them very susceptible to construction damage.

In each soil, investigations were carried out in the Bt horizon, since the accumulated clay in this zone increased the risk of construction damage. Each soil was tested at a moisture content near the plastic limit, which is close to the water content of most efficient compaction for the ranges of compactive effort studied (Felt, 1965; Sowers and Sowers, 1970; Cohron, 1971). Since dry soils should be much less subject to compaction (Bouma, 1975a), each soil was also tested at a moisture content much drier than the plastic limit.

Of the five field trials conducted (Table 5-1), three were carried out at Arlington Experimental Farms on Plano silt loam: one with soil moisture near the plastic limit and a low level of wheel traffic; a second also near the plastic limit but with a higher level of wheel traffic; and a third on dry soil with the higher level of wheel traffic. Of two trials at Ashland on Ontonagon silty clay loam, one took place with the soil near the plastic limit and the other on dry soil, both with the higher level of wheel traffic.

Table 5-1. Matrix diagram of soil-treatment combinations studied.

	Treatments					
				Wheel traffic		
	Trial* number	Hand exposed	Machine excavated	Two passes	Four passes	Six passes
Plano soil						
Moist	P1-26	X	X	X	X	X
Dry	P1-19	X	X	X	X	X
Ontonagon soil						
Moist	On-20	X	X	X	X	X
Dry	On-12	X	X	X	X	X
				One pass	Two passes	Three passes
Plano soil						
Moist	P1-24	X	X	X	X	X

*Trial number reflects soil series (P1 - Plano, On- Ontonagon) and initial moisture content.

Experimental Procedure

Soil Characterization--

One profile at each study site was described using standard soil survey procedures and nomenclature (Soil Survey Staff, 1951). When morphology varied within or between the separate excavations at a site, this was noted.

Plastic and liquid limits (Atterberg limits) were determined by standard methods (Sowers, 1965). Plasticity index for each site was obtained by subtracting plastic limit from liquid limit, and was used to determine clay activity (Sowers and Sowers, 1970). Mechanical analyses were determined by the hydrometer method (Day, 1965). General clay mineralogy for the soils studied was obtained from Soil Conservation Service soil series description sheets, and checked by these clay activity figures.

Hydraulic conductivity characteristics of the two soils studied were taken from Baker (1976) and from field data obtained for the "Application of Household Wastewater" segment of this project.

Construction Trials--

The two dry soil field trials reflected then-current field moisture conditions. For any trial near the plastic limit, the plot was irrigated for several days with a sprinkler, then allowed to drain for two more days before excavation. Soil water content was monitored regularly by hand and by gravimetric determination (Gardner, 1965).

For each field trial, a backhoe-equipped tractor (Figs. 5-3 and 5-4) excavated a rectangular, five-by-ten meter simulated absorption bed. The depth of the bed was at the middle of the Bt horizon. The depth variability of any excavated bed was no more than 10 cm.

The tractor with backhoe drove into, through, and out of each excavation on soil ramps at either end, creating three separate wheel tracks, with the middle track formed by the overlap of passes on each side of the bed (Fig. 5-5). By varying the number of passes on each side, different degrees of wheel traffic were imposed on each track. The slow speed of the backhoe minimized wheel slippage, though neither was measured.

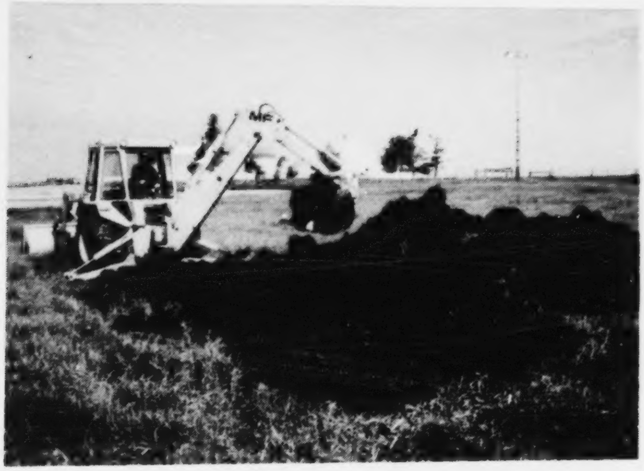


Figure 5-3. Tractor-mounted backhoe excavating simulated absorption bed.

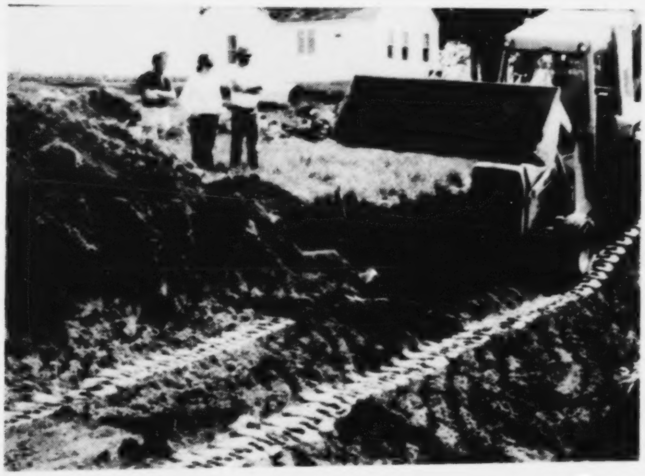


Figure 5-4. Backhoe equipped tractor driving into excavation. Wheel tracks for previous pass are visible.

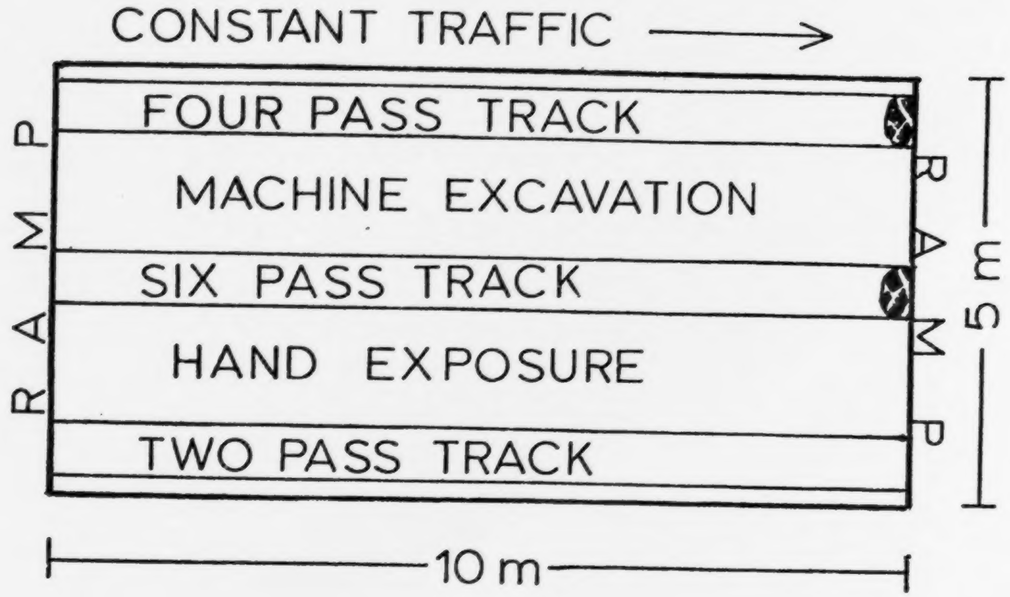

CONSTANT TRAFFIC
FOUR PASS TRACK
MACHINE EXCAVATION
SIX PASS TRACK
HAND EXPOSURE
TWO PASS TRACK
RAMP
RAMP
5 m
10 m

Figure 5-5. Plan view of excavated field trial, showing arrangement of the five treatments. Direction of all wheel traffic was held constant.

Sampling--

A 60 cm wide trench was excavated an additional 50 cm deep across the tracked bed for sampling and equipment installation, and to provide drainage. Samples were obtained from the bed to determine moisture content, liquid and plastic limits, and particle size analysis. For pore size distribution, bulk density, and thin section analysis, a hydraulic probe obtained undisturbed 7.62 cm x 5.7 cm cores. When possible, four core samples were collected from each of the five treatments in each trial. These five treatments corresponded to those used for infiltration measurements, and included three wheel-traffic treatments (either one, two, and three passes, or two, four, and six passes), the machine-excavated surface, and a portion of the bed which had been spaded and "picked" with a knife to expose undisturbed soil structure. A pocket-sized penetrometer measured penetration resistance for each of these five treatments.

Infiltration Tests--

Ten infiltration rings (Bouma et al.,1974a) were installed, with two 25-cm diameter rings on each of the five treatments. In each case, the soil surface characteristics beneath a given ring typified the entire treatment area. Thus, unusual cracks, lumps, and holes were avoided, and surfaces as level as possible were selected.

After ring placement, a 25-cm diameter cylindrical soil pedestal was carved out beneath each ring, usually to a depth of 30 cm. The 30-cm pedestal height ensures one-dimensional downward flow during the test (Baker, 1977).

The walls of the pedestals frequently intersected pebbles and stones in the soil matrix. Wherever possible, these coarse fragments were left embedded in the pedestal sidewalls. When fragments were removed, the resulting cavities were filled with dental plaster.

The carved pedestals were coated several times with plaster both for support and to retain water. Gaps between infiltration rings and soil pedestals were sealed by gently tamping a 3 mm-wide strip of soil around the inside surface of the ring.

The infiltrative surfaces of most pedestals were carefully cleaned of loose soil with a "Shop-Vac" vacuum cleaner; however, the surface of the machine-excavated treatments of all five trials, and the wheel-tracked treatments in the dry Ontonagon soil (On-12) were too fragile to be vacuumed. Because these infiltration tests were used to find saturated conductivity, the gypsum crusts normally used in the crust test procedure (Bouma et al.,1974a) were not applied to the pedestal surfaces.

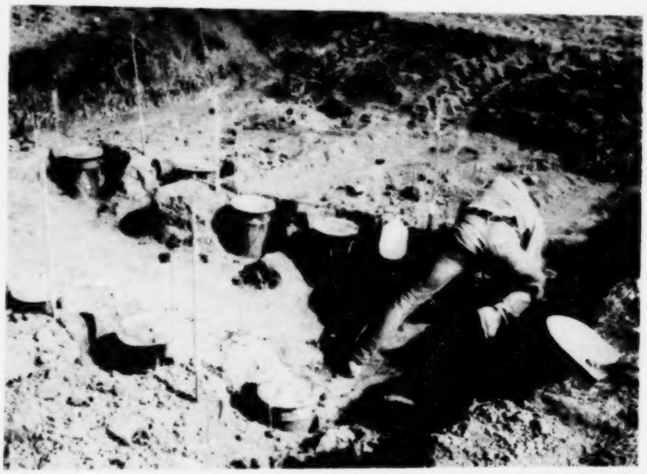


Figure 5-6. Installation of infiltration rings on excavated soil pedestals. Plaster coats have not yet been applied to pedestals.

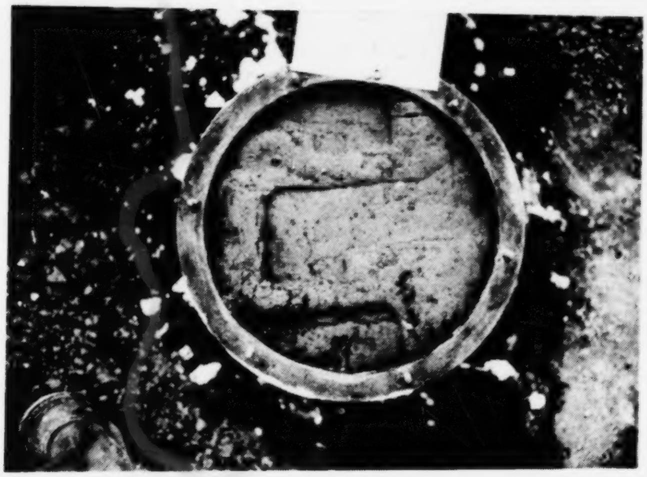


Figure 5-7. Top view of infiltration ring mounted on excavated soil pedestal. Note wheel-tracked infiltrative surface.

After cleaning, all infiltration test surfaces were photographed so that macropores and cracks could subsequently be related to infiltration rates.

In most cases, two pencil-sized tensiometers were inserted into each soil pedestal, about 2 cm below the infiltrative surface, to monitor soil moisture tensions induced by any surface crust or restrictive layer. In a very few cases, coarse fragments protruding from the sides of a soil pedestal prevented the metal infiltration ring from being fully seated on the pedestal. Tensiometers installed in the pre-drilled holes in these rings would have disrupted the soil surface.

Water flowed from a Mariotte-equipped burette through a plastic tube to the infiltration ring cover plate, and then to the test pedestal (Fig. 5-8). Each burette was elevated so as to produce a slight hydraulic head on the soil surface. Optimally, this head should be about 3 mm (Bouma et al., 1974a); however, parts of surfaces in some pedestals received hydraulic heads of up to 3 cm due to slopes and irregularities in those surfaces.

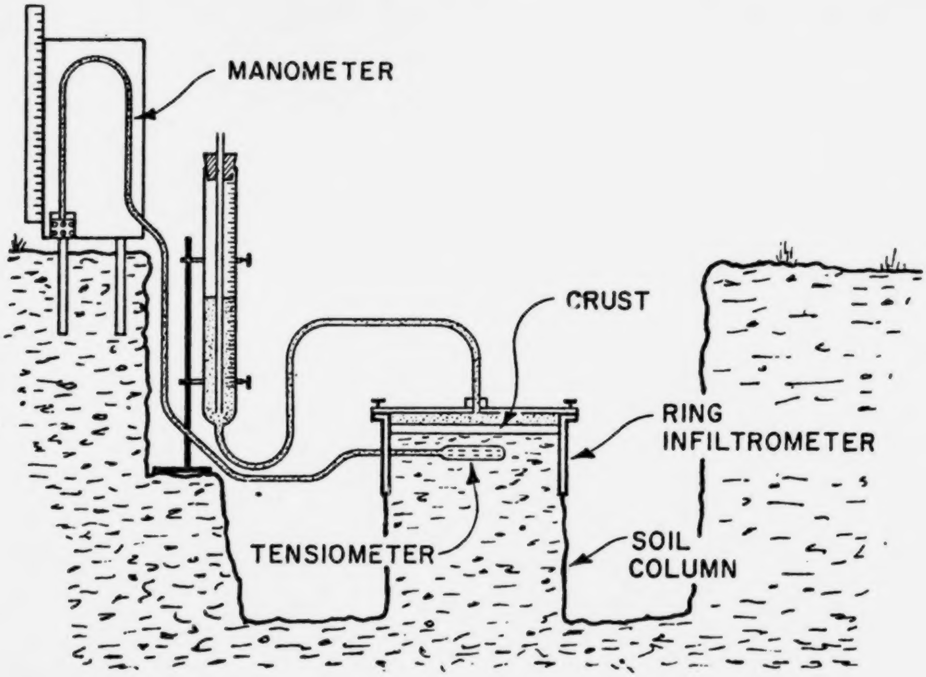


Figure 5-8. Schematic diagram of infiltration apparatus.

Before measurements were made, each soil pedestal was wetted and drained at least twice to swell expanding clay minerals. The soil moisture tension in the pedestals remained below 100 mbar for three to four days. Any cracks in the plaster coats on the pedestals, caused by clay swelling, were patched during the drainage periods. Tap water was then applied at a head of about 3 mm until an equilibrium infiltration rate was reached. Results were expressed in terms of volume of water delivered per unit time. Tensiometer readings were taken throughout infiltration.

After infiltration tests, the same soil pedestals were used to gauge the effects of simple techniques to restore the infiltrative capacity of compacted surfaces. Restoration was attempted at three sites; these were the moist and dry Plano soil (Pl-27, Pl-19) and the moist Ontonagon soil (On-20), all under the high level of wheel traffic. At each of these three sites, restoration was employed on all wheel-traffic treatment pedestals and on one machine-excavated surface. For one pedestal from each of these four treatments, the infiltration ring was left in place and the vacuum cleaner used to remove about 2 cm of soil. No hand "picking" was necessary; the vacuum cleaner suction was sufficient to lift soil away. Tensiometers were left in place in these four pedestals.

One soil pedestal from each of the three wheel-traffic treatments was severed just below the lower edge of its metal infiltration ring. Each ring was then reset on its pedestal, and its tensiometers were re-installed. After vacuuming to remove any traces of smearing caused by cutting the pedestals, these restored pedestals had.surfaces about 10 cm below their original wheel-tracked surfaces. Infiltration rates for these restored pedestals were determined following the procedure used for the original surfaces.

Pore Size Distribution Determination--

Pore size distribution was determined by the hanging water column-porous plate method of Vomocil (1965), as modified by Bouma et al. (1974). Core samples in 7.65 cm x 5.7 cm metal cylinders were trimmed to length, without smearing. Cores of the undisturbed soil from each trial were trimmed at both ends, but cores of wheel-traffic and machine-excavation treatments were trimmed on bottom surfaces only. Since the untrimmed top surfaces of these cores were seldom plane, each core was positioned within its cylinder so as to balance the volume of all depressions below the top edge of the cylinder with an equal volume of soil protruding above the cylinder. The bottom surface of each core was then trimmed flush. Core volumes for these treatments were thus approximately equal to cylinder volume, with errors in positioning probably not exceeding 3 mm (5%).

A 10-cm square of cheesecloth was taped to the bottom of each cylinder to support the core during handling. The cores were then placed on wet sponges in a basin. Over the course of several days, the water level in the basin was raised until it reached just below the top edge of the cylinders. This method yields samples which are very close to saturation (Bouma et al.,1974a; Jaynes, 1978). After the saturated weight was obtained, each core was placed in a 10-cm diameter fine-grained Buchner funnel connected to a water-filled burette. A layer of very fine sand assured good contact between sample and plate. Initial equilibrium was established by keeping the top of the water column level with the lower surface of the porous plate, about 4 cm below the center of the core. Subsequent equilibrations were made at tensions of 20, 40, 60, 80, and 100 cm of water.

After the final equilibration, each core was weighed, oven-dried, and weighed again. Percent porosity and bulk density were calculated.

For each site, porosities have been plotted cumulatively with increasing tension and decreasing pore size. Non-capillary pores are not measured by this porous plate method, so the reported porosity percentages reflect only pores smaller than about 0.75 mm diameter, corresponding to the initial tension of 4 cm of water.

Corrections in bulk volume were necessary for the samples from the first Ontonagon soil trial (On-12). These cores of initially dry soil swelled upon saturation, so bulk volume was adjusted after measuring how high the soil rose above the top edge of each cylinder.

Low-power Microscopy--

Pieces of the oven-dry cores were impregnated with a plastic resin. Sections sliced from the impregnated samples were ground smooth, and were then examined with a low-power binocular microscope. Qualitative estimates were made of porosity and pore-size distribution, and of the degree of orientation of pores and soil structure.

Trenching Machine Trial

In a supplementary study, one field trial using an endless-chain, ridable trenching machine was conducted at the Arlington Experimental Farm on Plano soil. The machine excavated a 1 m deep, 20 cm wide trench across both a dry (18% moisture) area and a moist (29% moisture) area. Subsequent hand excavation exposed one sidewall in each area. Penetration measurements, visual observations, and photographs were taken of each sidewall. In addition, 7.62 cm x 5.7 cm horizontal cores were obtained from the sidewalls to measure pore-size distribution and hydraulic conductivity. Results of this supplementary study will be submitted at a future date.

RESULTS AND DISCUSSION

Soil and Machine Characteristics

Data on the characteristics of the Plano and Ontonagon soils, including moisture content at the time of excavation and results of textural and Atterberg limits determinations, are presented in Table 5-2.

Detailed profile descriptions of the two field study soils are found in Tables 5-3 and 5-4.

Table 5-5 presents the characteristics of the backhoe-equipped tractors used during the five field construction trials.

Visual Effects of Construction Machinery

Excavation--

Machine excavation at all sites produced clearly visible smeared surfaces. The smooth-edged backhoe bucket which excavated one of the Plano soil sites (Pl-24) left a rather uniform smeared surface over the entire bed area. This smeared surface was not continuous, but was made up of 2 to 6 cm wide plates of soil which had very smooth, slick top surfaces.

These plates were typically curled or peeled back, apparently by bucket drag forces, exposing underlying soil which seemed to have a relatively unaltered structure. Subsequent low-power microscopic examination of this underlying soil showed that it had actually suffered some reduction in porosity, particularly in the larger pore sizes. Remaining pores tended to be oriented in a horizontal direction, parallel to the direction of shearing.

Table 5-2. Physical characteristics of Plano silt loam (Typic Argiudoll, fine-silty, mixed, mesic) and Ontonagon silty clay loam (Glossic Eutroboralf, very-fine, mixed).

Soil	Plano			Ontonagon	
Horizon	B2t			B22t	
Depth	75 cm			45 cm	
	Trials*			Trials*	
	Pl-24	Pl-26	Pl-19	On-12	On-20
Initial moisture content (%)	24	26	19	12	20
Plastic limit (%)	27	26	24	22	14
Liquid limit (%)	44	44	42	41-50	42
Plasticity index	17	17	18	19-28	38
Clay activity	0.61	0.59	0.69	0.34-0.50	0.62
Textural analysis					
Sand (%)	3	5	9	7	18
Silt (%)	69	66	66	37	37
Clay (%)	28	29	26	56	45
Texture	Silty clay	Silty clay loam	Silty clay loam	Clay	Clay
Equipment (see Table 5-5)	John Deere JD 500	Massey Ferguson 40-B		Allis Chalmers I 600	

*Trial number reflects soil series (Pl - Plano, On - Ontonagon) and initial moisture content.

Table 5-3. Profile description of Plano silt loam.
Location: Arlington Experimental Farm, Dane County, Wisconsin.
Classification: Typic Argiudoll, fine-silty, mixed, mesic.

Horizon	Depth (cm)	Description
A1	0-23	Very dark brown (10YR 2/2) silt loam; moderate, medium and coarse granular structure; friable, many very fine and fine and common medium roots; clear, smooth boundary.
A3	23-30	Dark yellowish brown (10YR 3/4) silt loam; moderate fine and medium subangular blocky structure; friable; many very fine and fine and common medium roots; many medium, continuous, vertical tubular pores with thick very dark brown (10YR 2/2) coatings; clear, smooth boundary.
B1t	30-53	Dark yellowish brown (10YR 4/4) silt loam; moderate fine and medium subangular blocky structure; friable; common thin continuous dark yellowish brown (10YR 3/4) argillans; common fine roots; many medium, continuous, vertical, tubular pores with thick very dark brown (10YR 2/2) coatings; gradual,smooth boundary.
B2t	53-86	Dark yellowish brown (10YR 4/4) silty clay loam; moderate medium and coarse blocky structure, breaking to fine and medium blocky structure; firm; many thick continuous dark brown (10YR 3/3) argillans; few fine roots; many medium, continuous, vertical, tubular pores; clear, smooth boundary.
B3t	86-102	Dark yellowish brown (10YR 4/4) silty clay loam; moderate medium and coarse prismatic structure breaking to medium and coarse block structure; firm; few thick patchy and common thin patchy dark yellowish brown (10YR 3/4) argillans; few fine roots; common medium, continuous, vertical tubular pores; clear, smooth boundary.
C1	102-117	Yellowish brown (10YR 5/4) silt loam; moderate coarse prismatic structure; friable; common medium, continuous, vertical, tubular pores; clear, smooth boundary.
IIC2	117-150	Brown (10YR 5/3) sandy loam; about 10% coarse fragments by weight; single grain; loose.

*All colors are for moist soil.

Table 5-4. Profile description of Ontonagon silty clay loam.
Location: Ashland Experimental Farm, Bayfield County, Wisconsin
Classification: Glossic Eutroboralf, very-fine, mixed.

Horizon	Depth (cm)	Description
A1	0-10	Dark reddish brown (5YR 2/3)* silty clay loam; moderate medium granular and fine and medium subangular blocky structure; firm; common fine and medium roots; clear, smooth boundary.
B21t	10-23	Reddish brown (2.5YR 4/4) clay; strong fine and medium blocky structure; common, thin, dark reddish brown (2.5YR 3/4) argillans; very firm; few thin reddish brown (5YR 5/4) coatings on some vertical ped faces; common fine and medium roots; common medium, continuous, vertical, tubular pores; clear, wavy boundary.
B22t	23-56	Reddish brown (2.5YR 4/4) clay; moderate medium prismatic structure, breaking to strong fine and medium blocky structure; many continuous moderately thick dark reddish brown (2.5YR 3/4) argillans; very fine; common fine and medium roots; common medium, continuous, vertical, tubular pores; gradual, smooth boundary.
C	56-100	Reddish brown (2.5YR 4/4) clay; weak medium prismatic structure; breaking to moderate medium blocky structure; very firm; few medium roots; few medium, continuous, vertical, tubular pores.

*All colors are for moist soil.

Table 5-5. Characteristics of backhoe-equipped tractors used.

	Soil trials*		
	P1-24	P1-19 P1-26	On-12 On-20
Tractor make	John Deere	Massey-Ferguson	Allis Chalmers
Model	JD 500	40 B	I 600
Weight on front axle (kg)	1240	930	860
Weight on rear axle (kg)	5560	4160	3840
Total weight (kg)	6800	5090	4700
Rear tire size (cm)	35.6x96.5	44.5x61	43x61
Rear tire pressure (kg/cm^2)	1.76	2.81	2.11

*Trial numbers reflect soil series (Pl - Plano, On - Ontonagon) and initial moisture content.

All other test sites were excavated with a tooth-edged backhoe bucket. On the moist Plano soil, these teeth left prominent marks with very smooth, slick surfaces. The tooth marks in the dry Plano soil were less slick, but still quite smooth. In both of these trials, the lifting or peeling of machine-produced soil plates was less evident than in the smooth bucket case, though more of this peeling did occur between bucket teeth than under them.

Low-power microscopic examination of these tooth marks showed thin (1 to 2 cm) compact surface layers, with the few remaining pores strongly oriented horizontally. Such compact layers were largely absent between tooth marks, and when present, were much more porous than those under tooth marks. Compaction appeared to be slightly more prevalent in the moist soil (Pl-26) than in the dry soil (Pl-19).

Prominent tooth marks with smooth, slick surfaces were produced by a tooth-edged backhoe bucket on the moist Ontonagon soil. A small amount of peeling of slick plates occurred in the tooth marks; much more was evident between the tooth marks. Low-power microscopic examination revealed compaction patterns similar to those of the Plano soils excavated with tooth-edged buckets, with compaction most evident under tooth marks and less evident between. Compaction appeared to be less than in the moist Plano soil, and about equal to that in the dry Plano soil.

Tooth marks in the dry Ontonagon soil (On-12) were much less prominent than in all other trials. These marks were rough-textured, and only occasionally appeared to be shiny or slick. No peeling action was apparent. Between tooth marks, the dry soil was fairly cleanly cleft along natural structure planes. No smearing or peeling was evident. All excavation surfaces at this site were covered by a loose layer of hard, dry clay aggregates which ranged from 1 to 3 cm in diameter, consisting primarily of strong, fine and medium blocky peds from the B21t horizon.

Though smearing was almost entirely absent at this site, low-power microscopic analysis revealed that some compaction had occurred and large pores had been reduced in number. Compaction was confined to a very thin layer beneath the tooth marks. No compaction was evident between the marks.

During these trials, smearing and compaction by excavation machinery were much more prevalent on moist soils than on dry soils, and more evident on the Plano soil than on the Ontonagon soil. The dry silty clay loam Plano soil was smeared much more strongly than was the dry clayey Ontonagon soil. The principal effect of compaction was the reduction of the volume of large pores. In compacted layers, much of the remaining porosity tended to be oriented horizontally. Compaction effects were confined tb the upper 1 to 2 cm of soil.

At most sites, there was a fairly significant amount of peeling of platy structures by dragging bucket surfaces. This was not evident at the dry Ontonagon site.

Wheel Traffic--

Wheel traffic left very clear tire impressions (Fig. 5-9) in the moist and dry Plano soil and the moist Ontonagon soil. The tracks were very smooth and slick in moist soil, while tracks in the dry Plano soil were fairly smooth but not slick. Surface porosity was greatly reduced.

Tire tracks in the dry Ontonagon soil were discernible, but much less clear than those in other trials (Fig. 5-10). The loose, dry clay aggregates were pressed together slightly beneath the tires, producing wheel tracks which were much more porous than the underlying natural soil.

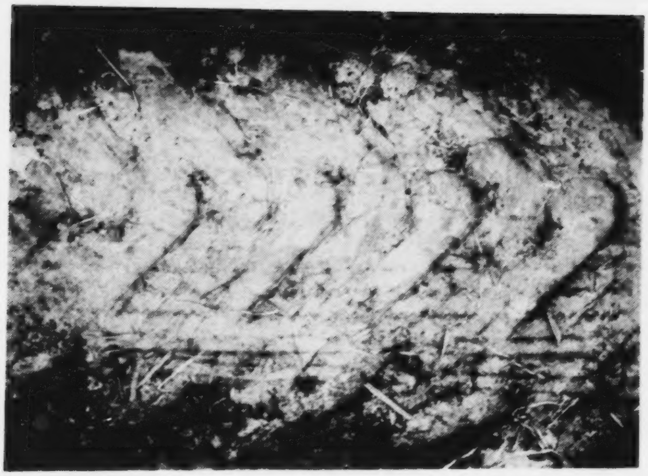
Except for the dry Ontonagon soil, low-power microscopic examination confirmed that wheel traffic reduced porosity in both soils studied. Furthermore, these samples exhibited a pronounced platy structure which had resulted from the wheel traffic. Depth and intensity of the porosity reduction increased with increasing traffic passes. Porosity appeared to be lowest at the surface and to increase to normal with depth. Large pores were reduced by wheel traffic, and much of the remaining porosity was oriented in a horizontal manner.

No compaction effects were observed in the natural soil underlying the loose aggregate layer at the dry Ontonagon soil site. Aggregates and soil were able to resist wheel traffic without serious deformation.

Chancellor et al. (1962) found that piston compression produced the greatest reduction in porosity at a depth of about 4 cm, rather than at the immediate surface. No such subsurface layer of minimum porosity was observed in any of the wheel traffic samples of the current study. This may reflect the action of repeated, relatively low intensity wheel traffic passes. The study of Chancellor et al. (1962) applied single, high-pressure, piston actions to soils. It is likely that shearing forces resulting from tire flexure and from vehicle thrust helped to mask any subsurface layer of minimum porosity in this study, by increasing compaction at the soil surface.

It is possible that a compact subsurface layer was produced by wheel traffic, but went undetected because it lay in the zone between surface and subsurface core samples. However, it is likely that at least a hint of decreasing porosity would have been found at the bottom of the surface cores in this case. Such a decrease in porosity was not observed. Further examination of infiltration test soil pedestals produced no evidence of any subsurface layer of minimum porosity. Porosity in these soil pedestals appeared to increase to normal with depth.

Wheel traffic reduced porosity at all study sites, except for the dry Ontonagon soil. These reductions were associated with very clear tire tread impressions. The most severe reductions occurred in moist soils, where the tire tracks were very smooth and slick in appearance. Porosity reductions and traffic-produced platy soil structure decreased with depth. Depth and intensity of these effects increased with increasing traffic passes and initial moisture content, and with decreasing clay content and strength of expression of soil structure.



Firgure 5-9. Wheel-tracked surface from moist Ontonagon soil trial (On-20). Surface porosity has been greatly reduced; compare with Fig. 5-10.

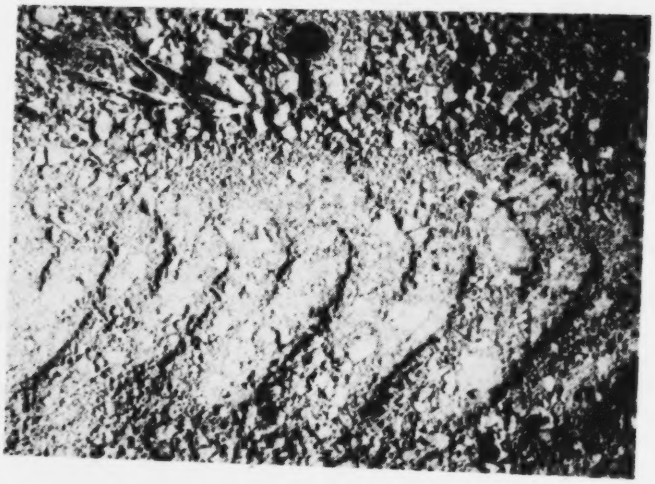


Figure 5-10. Wheel-tracked surface from dry Ontonagon soil trial (On-12). The loose, hard aggregates have maintained a very porous condition; compare with Fig. 5-9.

Compaction and smearing by machine excavation and wheel traffic were most severe when these actions produced very smooth, slick surfaces, and thus weren't severe in moist soil. The more weakly structured Plano soil rendered it more susceptible to compaction than the strongly structured Ontonagon soil. Even when dry, the Plano soil exhibited substantial reductions in porosity.

Where porosity reductions occurred, much of the remaining porosity tended to be oriented in a horizontal manner, and the soils exhibited a machine-produced platy structure. These changes in porosity and soil structure would be expected to reduce hydraulic conductivity at and near saturation.

Influence on Pore Size

Compared to the hand- and backhoe-exposed infiltrative surfaces, wheel traffic reduced the proportion of large pores in the soil system except for trial On-12. This is seen in Figures 5-11 through 5-15, which show cumulative porosity versus soil moisture tension and pore size. A point on any of these curves indicates the total volume of all pores larger than or equal to the given diameter.

In any trial, the samples showing the greatest cumulative porosity have suffered the least compaction.

Plano Soil--

Pore size distribution results for site Pl-24 reflect several trends which recur at most other sites (Fig. 5-11). Throughout its length, the porosity curve for the machine-excavated surface is higher than that for the natural soil. This suggests that any compactive effects of the excavation action on porosity were negated by a lifting, loosening, or peeling of the upper 1 or 2 cm layer of soil, even though the soil beneath was somewhat compacted. Low-power microscopic examination of machine-excavated surfaces supported this idea.

In contrast, wheel traffic produced a pronounced decrease in soil porosity which was most evident in the larger size pores, those larger than about 75 microns (40 cm of water). For pores smaller than 50 microns, the slopes of the curves for the compacted samples are similar to the curve for the natural soil, indicating that pore volumes in this pore size range were not altered greatly by wheel traffic.

Porosity decreases (Fig. 5-11) are noticeable in the one-pass case, though most of the change occurs in pores larger than 150 microns diameter. Porosity reductions for two and three passes of the tractor are much greater and are evident through a wider range of pore size, down to 50 microns diameter. The volume of small pores (30 microns) was increased. While total porosity was decreased, many large pores were squeezed down to small size, increasing the amount of small pores (Foth, 1978).

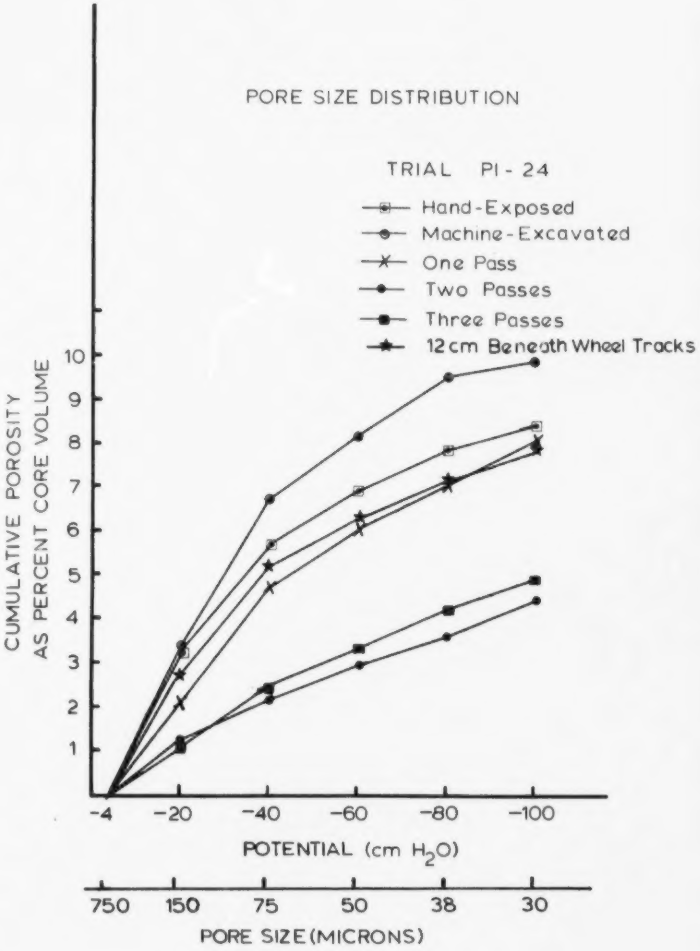


Figure 5-11. Pore size distribution data from Plano soil trial P1-24.

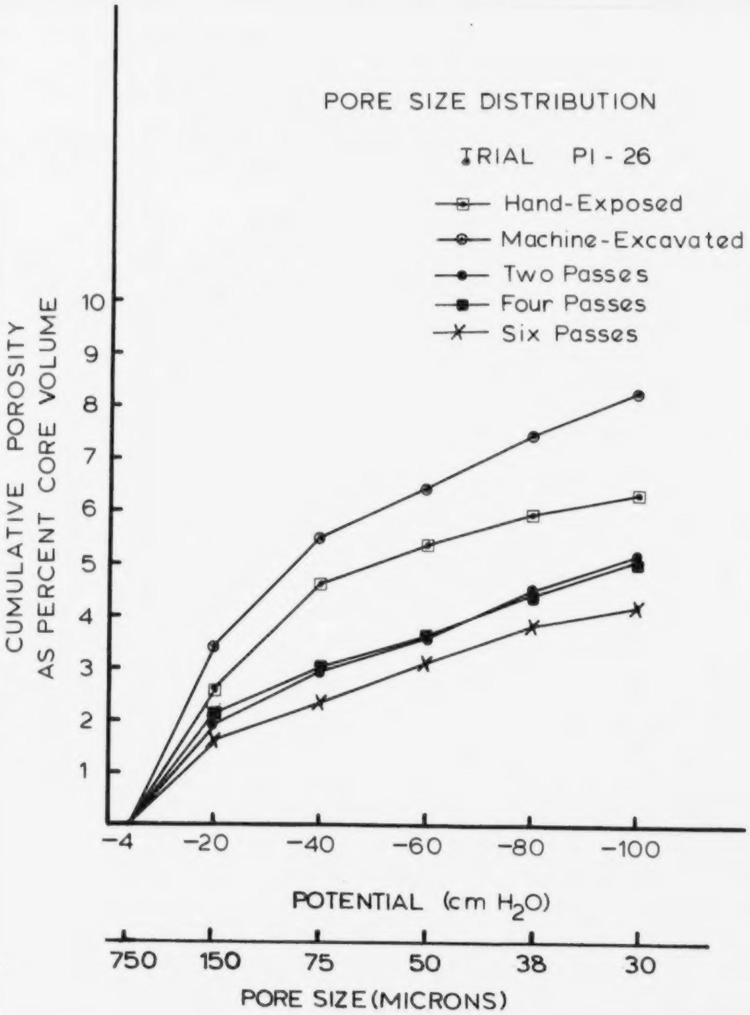


Figure 5-12. Pore size distribution data from Plano soil trial P1-26.

Core samples taken 12 cm below the wheel-tracked surfaces showed porosities slightly lower than those of the natural soil (Fig. 5-11). While this difference may have been caused by the wheel traffic, compaction effects were not observed to extend this deep during low-power microscopic examination. This difference was likely a reflection of the less porous natural soil structure at this depth. These cores reached into the B3t horizon, which contained fewer medium, continuous, tubular pores than the B2t horizon, and which had a prismatic structure, in contrast to the blocky B2t horizon.

The other Plano soil trials (P1-19 and P1-26) differed from the first in having a somewhat lighter tractor (Table 5-5) driving over the excavated bed floor twice as often (two, four and six times). Calculated ground pressures were also slightly lower.

The soil moisture content at P1-26 was 26% (Table 5-2). As in the first trial, the machine-excavated surface was more porous than the natural soil (Fig. 5-12). The flat slopes of the porosity curves of all compacted treatments indicate that the treated soils had fewer pores larger than 75 microns than the natural soil. An increase with wheel traffic in pores smaller than 38 microns is shown by a narrowing of the distance between these curves and the curve for the hand-exposed surface. As before, large pores were squeezed down to small size, increasing the total volume of small pores.

In the driest Plano soil trial (P1-19), the machine excavated surface showed increased porosity as compared with the natural soil (Fig. 5-13). Porosity reduction due to wheel traffic was in a narrower range of large pore sizes than in the P1-26 trial. Also, increases in small pores were less noticeable than in P1-26. Apparently, the drier soil in P1-19 resisted vehicle compaction more than the moist soil did in P1-26. This result would be expected on the basis of soil compaction theory (Sowers and Sowers, 1970).

The position of the four-pass porosity curve (Fig. 5-13) is apparently due to a shallower depth to glacial till beneath this wheel track than other parts of the P1-19 excavation. The four-pass treatment cores contained several sandy lenses, and the textures at the lower ends of these cores were noticeably coarser than those of other treatments. The higher than expected porosity may also have been caused by a small compaction response of this coarser material.

The silty clay loam B2t horizon of the Plano soil was easily compacted by wheel traffic over a wide range of moisture contents. Compaction greatly reduced the volume of large pores and tended to leave remaining pores oriented horizontally. Both of these effects would be expected to reduce hydraulic conductivity at and near saturation. Compaction was not found to extend beyond 10 cm depth.

Machine excavation produced thin (1 to 2 cm) smeared and compacted surface layers. Porosity reductions in these layers were offset by a lifting or peeling of many of these platelike structures, but layers of reduced porosity were usually present beneath. Such compaction was fairly uniformly spread under a smooth-edged backhoe bucket, but beneath a

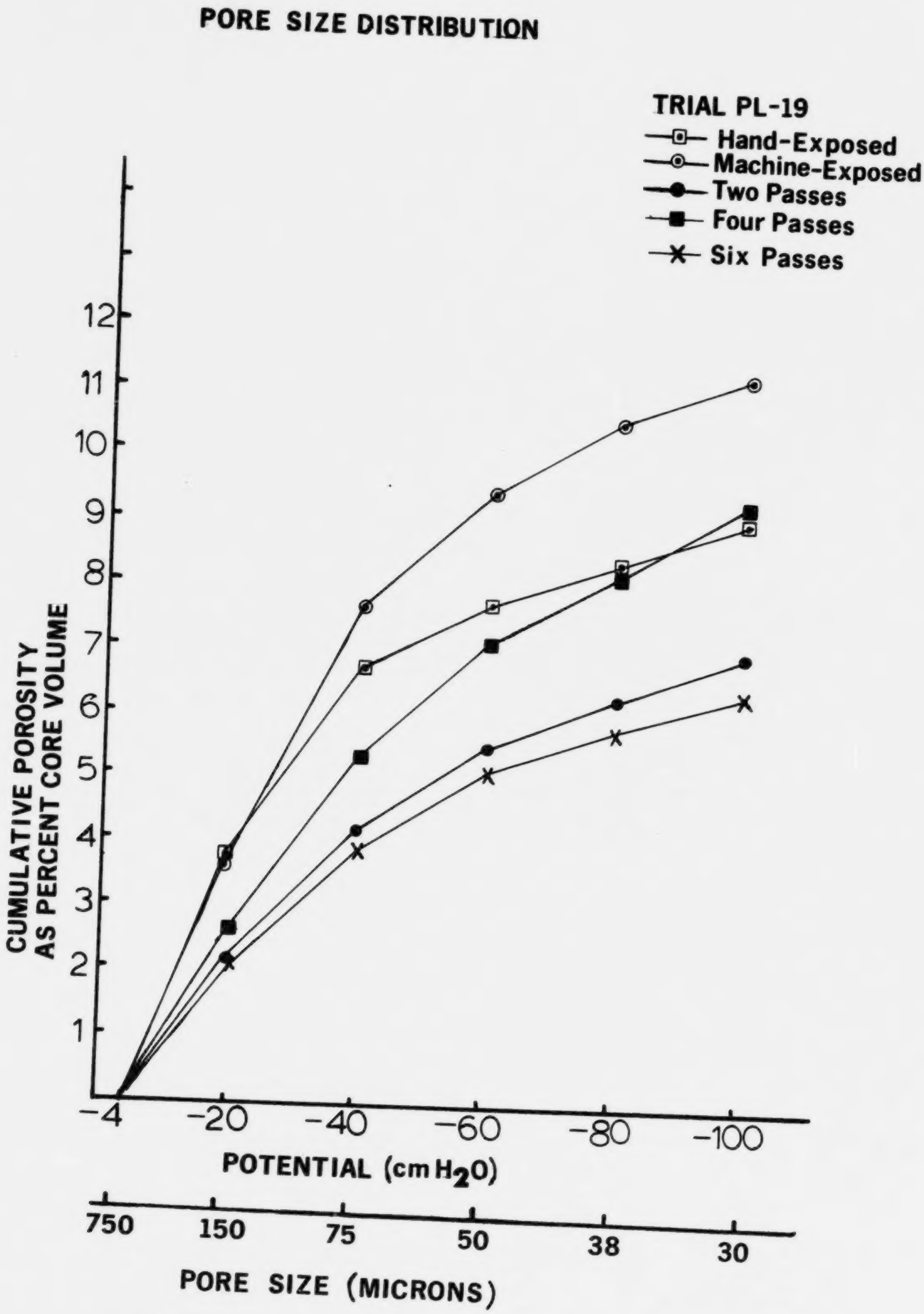


Figure 5-13. Pore size distribution data from Plano soil trial Pl-19.

tooth-edged bucket, compaction was concentrated in the tooth marks, in response to forces concentrated there. Regions between tooth marks were usually free of serious compaction. Thus, substantial areas might remain open to normal flow in the case of the tooth-edged bucket, while some flow restriction appears to be spread over the entire area excavated with a smooth-edged bucket.

Responses of other silty soil horizons to the shearing and compressive forces imposed by these construction techniques would likely be similar to those of the Plano B2t horizon. Such horizons would need to be considerably drier than any of the Plano sites examined in order to have any chance of avoiding substantial reductions in large pores.

Ontonagon Soil--

Pore size distribution results for the dry Ontonagon soil trial (On-12) show an inverted pattern as compared with the Plano soil trials (Fig. 5-14). In this trial, the wheel traffic treatment surfaces actually exhibit higher porosity than the hand-exposed soil. Excavation of this site left a loose layer of hard dry clay aggregates on the bed floor. These gravel-like aggregates, which consisted primarily of strong, fine and medium blocky peds from the B21t horizon, were able to withstand wheel traffic with little deformation, leaving very porous wheel-track surfaces (Fig. 5-10).

The loose aggregates were removed during preparation of the hand-exposed surfaces, so porosities for this treatment represent those for the underlying intact soil.

The peculiar ordering of the wheel track porosity curves (Fig. 5-14), -- particularly the very porous condition of the six-pass surface -- appears to result from variable thicknesses of these hard dry aggregates over the natural soil under each track. When the six-pass curve is scaled such that its 30-micron diameter point coincides with that of the two-pass curve, the two curves correspond very closely. This suggests that the samples of these wheel tracks differ in the thickness of loose aggregates. The six-pass cores would almost exclusively consist of loose aggregates. The two-pass cores would contain a relatively small proportion of these aggregates, and a larger proportion of the underlying natural soil.

A similar interpretation can be made for the four-pass curve. Scaling this curve up to the 30-micron diameter point of the two-pass curve produces a fairly close fit, so this wheel track is presumed to have had a somewhat thinner layer of loose aggregates. Examination of the oven-dried cores has shown that the six-pass cores do contain the greatest thickness of loose aggregates, while the four-pass cores contain the least. However, the differences in the cores are not as great as might be expected from the porosity data.

In contrast to all other trials, the machine-excavated surfaces of On-12 exhibited a lower porosity curve than did the hand-exposed soil (Fig. 5-14). This suggests that the lifting, peeling action which apparently characterized excavation of the silty Plano soil trials was not sufficient to counteract compaction during excavation of the dry, clayey Ontonagon soil.

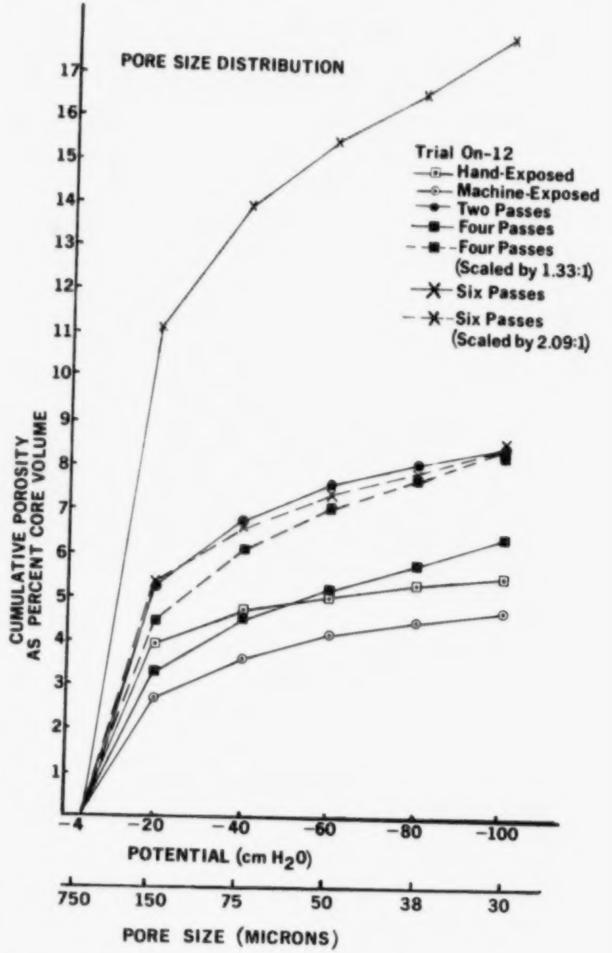


Figure 5-14. Pore size distribution data from Ontonagon soil trial On-12.

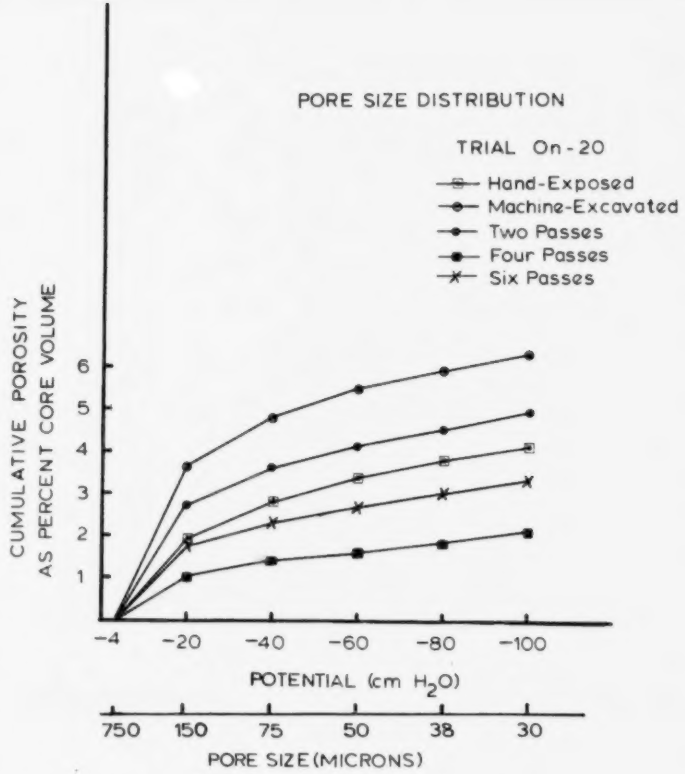


Figure 5-15. Pore size distribution data from Ontongon soil trial On-20.

In the moist Ontonagon soil trial (On-20), the porosity curve for the machine-excavated surface is substantially above the curve for the hand-exposed natural soil (Fig. 5-15). Since the moist clay was easier to excavate than the dry clay, less compactive effort may have been imposed on the moist soil during excavation. Though a lifting action may have produced the increased porosity in the moist soil, there was little visible evidence of it in the excavated surfaces of this trial.

The moist clay aggregates of Ontonagon soil trial On-20 were much more susceptible to deformation and compaction than were the dry aggregates of trial On-12. This is reflected in the relatively low porosity results of the wheel-traffic treatments of the moist trial (Fig. 5-15). However, the On-20 curves still show a peculiar ordering which seems to reflect the residual effects of the loose clay aggregates. Though moist, these aggregates were firmer than any of the silty aggregates in the Plano soil, and the tractor used during the Ontonagon soil trials was lighter than either of those used on Plano soil (Table 5-5). These differences may be enough to explain why the two-pass curve from On-20 is higher than that for the natural soil, and the six-pass curve is lowest (Fig. 5-15). The relative resistance to compaction during this trial is supported by the lack of any increase in volume of small pores for the wheel traffic treatments.

In four of the five field trials, major reductions in porosity were induced by wheel traffic. The most severe reductions occurred in the large pore sizes, and reductions generally became greater with increasing traffic. Porosity in the smallest pore sizes usually increased slightly with compaction. These results are in line with soil compaction theory (Sowers and Sowers, 1970).

Wheel traffic on a dry clay soil did not decrease porosity, because the soil was protected by a layer of hard, dry aggregates which were little deformed by the imposed forces. The underlying soil structure was easily able to withstand the forces transmitted through the loose layer. This suggests that no infiltration-limiting condition was created by wheel traffic at this site.

Some evidence of this aggregate durability also appeared in the moist clay soil trial. However, compaction of aggregates and the underlying soil did occur here, resulting in layers of reduced porosity which would probably impede infiltration.

Although the effects of initial water content were apparent on the clayey Ontonagon soil, they were less evident on the silty Plano soil, where substantial compaction occurred at all water contents examined. Strongly-expressed soil structure, such as that in the Ontonagon soil, appears to be a major factor in the ability of soils to resist compaction. Before silty soils and soils with more weakly-expressed structure exhibit appreciable maintenance of porosity under wheel traffic, they probably must be considerably drier than the dry moisture content studied here.

Effects on Infiltration Rate

Compared to the hand-exposed surfaces, wheel traffic reduced infiltration rates in all field trials, except for trial On-12. The data for these trials are presented in Tables 5-6 and 5-7. Figures 5-16 through 5-20 depict these data in graphical form. Each "initial" bar on these graphs represents the average rate of infiltration through the original treatment surfaces of two test pedestals.

In three of the figures (Fig. 5-17, 5-18, and 5-20), other bars represent the infiltration rates measured after restoration techniques had been employed. Here, each bar represents data from one restored pedestal. In these figures, results are expressed both as real infiltration rates and as "normalized" rates. The "100" point on each normalized scale has been set at the average value for the hand-exposure treatment. Thus, in some trials, data from some other treatments may be higher than on this scale.

Tables 5-6 and 5-7 present the complete normalized infiltration test data for all trials. Four values on these tables were eliminated, due to gross defects in test pedestal morphology and performance. These values are identified on the tables, and do not appear in Figures 5-16 through 5-20.

Field infiltration rates for the first Plano soil trial (Pl-24) show a slight apparent reduction for the machine-excavation treatment, when compared to the hand-exposed soil (Fig. 5-16). Some reduction is also apparent for the one-pass wheel track, and greater reductions are exhibited by the two- and three-pass tracks. These treatments show a possible reduction in infiltration of four- or five-fold. Higher values for two of the wheel track replicates are likely due to channel flow past the infiltration ring sidewalls, and to a 7 cm-diameter weathered stone found in one of the two-pass pedestals.

Machine excavation produced no discernible reduction in infiltration at the second moist Plano soil trial (Pl-26, Fig. 5-17) when compared to the hand-exposed surface. Increasing levels of wheel traffic produced decreasing rates of infiltration -- down to 2% of natural infiltration for the six-pass treatment. Restoration of these wheel-tracked surfaces increased the infiltration rates, and gave evidence of increasing depths of compaction with increasing traffic. Removal of 2 cm of compacted soil restored the two-pass surface; while 10 cm removal was necessary to restore the four-pass surface. Removal of 10 cm was not enough to restore the six-pass treatment; infiltration here was only restored to one-third of the rate for the hand-exposed soil, though this was still a major improvement over the compacted soil infiltration rate.

Table 5-6. Normalized field infiltration rates for hand-exposure, machine-excavation, and wheel-traffic treatments at field trial PL-24.

Treatment	P1-24
Hand-exposed	100 100
Machine-excavated	69 83
One pass	42 106
Two passes	130* 16
Three passes	16 28
Normalization base (100 = cm/day)	327

*Artificially high values produced by defects in test pedestals.

Table 5-7. Normalized field infiltration rates for hand-exposure, machine-excavation, and wheel-traffic treatments at four field trials.

	P1-26			P1-19				On-20		
		Restored			Restored				Restored	
Treatment	Initial	2 cm	10 cm	Initial	2 cm	10 cm	On-12 Initial[†]	Initial	2 cm	10 cm
Hand-exposed	89			101			30	40		
	110			99			170	181		
Machine-excavated	108	52		130		nd[‡]	160	108	15	
	134		nd	66	93		183			
Two passes	62	118		7		107	330	43	34	
	82		nd	32	39		316	189		5
Four passes	24	58		7	38		65	4		11
	62		99	3		222[§]	91	1	1	
Six passes	nd		35	41	82		157	2		0.6
	2	25		5		55	82	199[§]	0.2	
Normalization base 327 (100 = cm/day)		471			100		294		155	

[†] No restoration techniques employed at site On-12.

[‡] nd = no data.

[§] Artificially high values produced by defects in test pedestals.

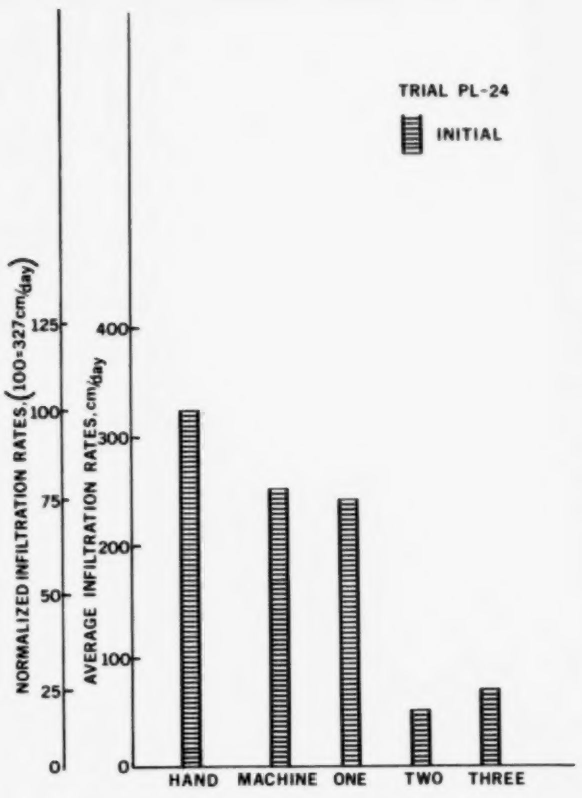


Figure 5-16. Infiltration test results from Plano soil trial P1-24.

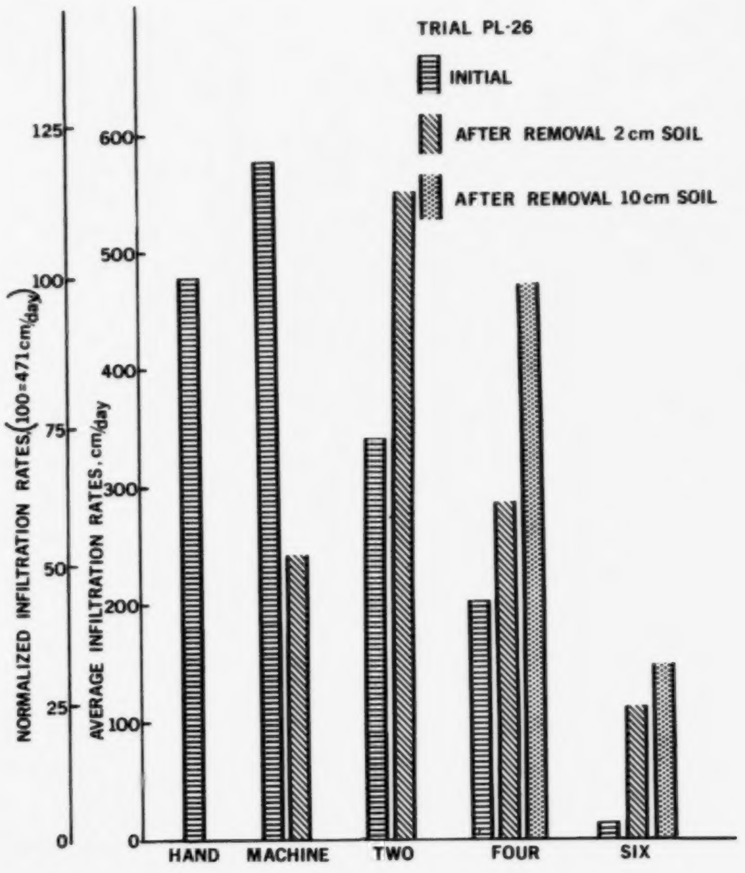


Figure 5-17. Infiltration test results from Plano soil trial P1-26.

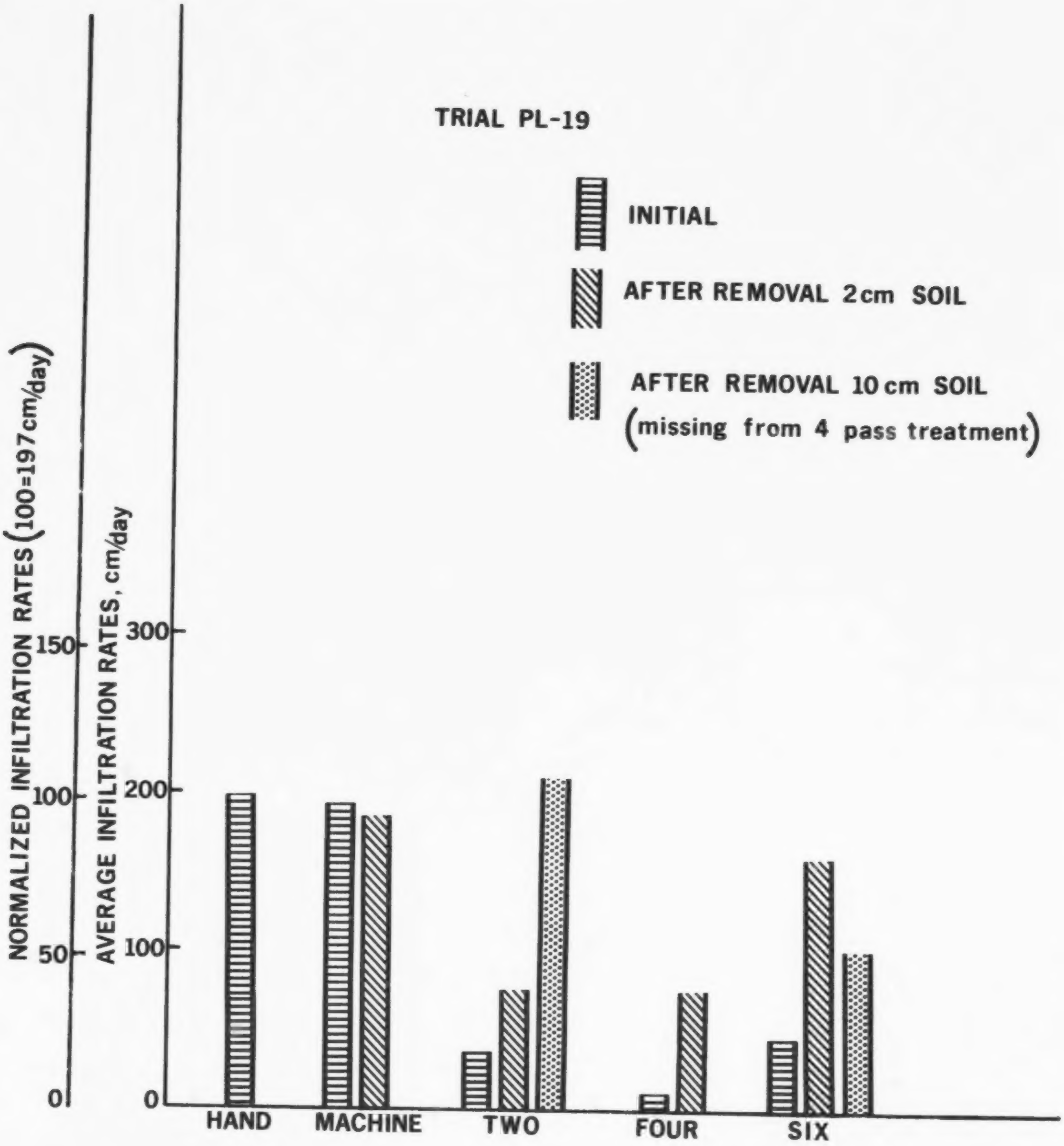


Figure 5-18. Infiltration test results from Plano soil trial Pl-19.

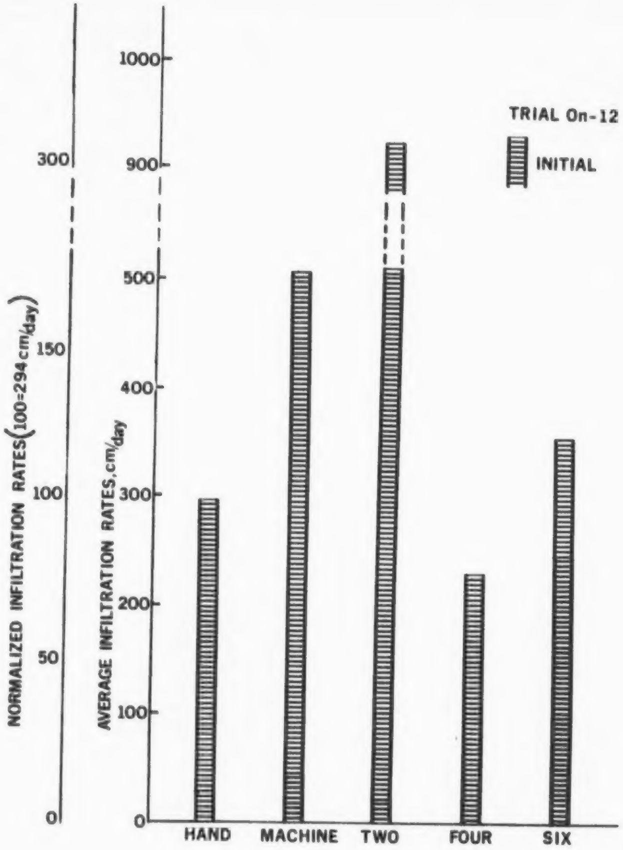


Figure 5-19. Infiltration test results from Ontonagon soil trial On-12.

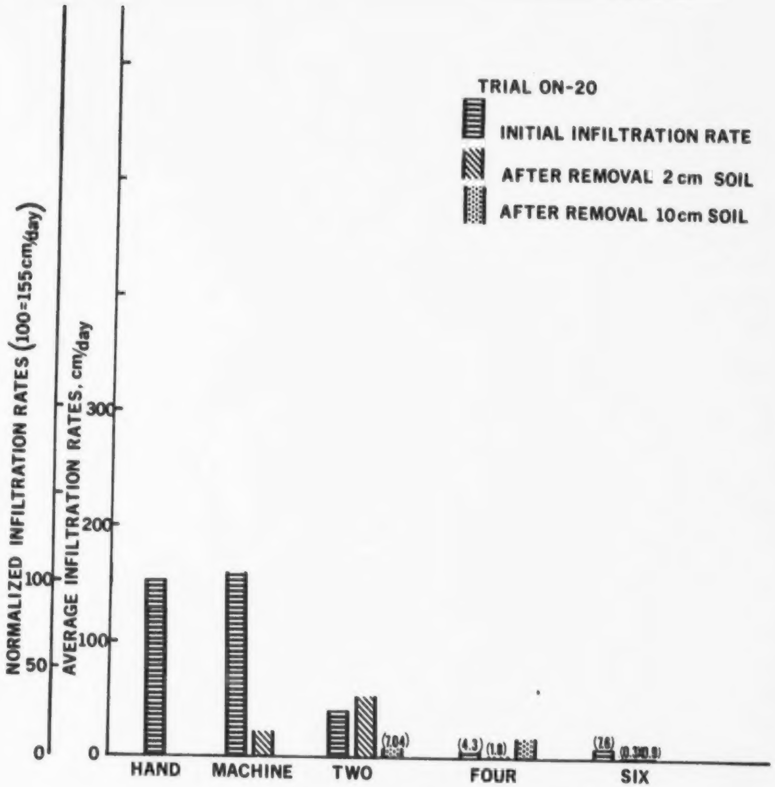


Figure 5-20. Infiltration test results from Ontonagon soil trial On-20.

Infiltration results for the restored machine-excavated surface are confusing (Fig. 5-17). This was the only pedestal of Plano soil for which the restored infiltration rate was slower than the initial rate. This suggests that a poor soil-ring seal for the initial run was improved for the second (restored) trial. This implies a "real" initial rate substantially lower than that for the natural soil, and that the machine excavation actually reduced infiltration through this pedestal. This interpretation contradicts the data for the other replicate of the treatment. Another possibility is that the slow restored rate represents the true (natural) rate of a dissimilar soil area, although examination of the pedestal provided no obvious evidence to support this idea.

Machine excavation at the dry Plano soil trial (Pl-19) produced ambiguous infiltration results, with about a 30% spread on either side of the hand-exposed surface rate (Fig. 5-18). Results for the wheel track treatments were much more uniform, with major reductions in infiltration produced by all levels of traffic. Rates of 3 to 7% of normal were common. Higher rates may have resulted from the experimental difficulties cited earlier, but may also represent real variations in compaction effects, since the rates for restored pedestals are in line with their respective initial rates. The very high rate for one restored four-pass pedestal resulted from the serious sidewall channeling which could not be completely stopped.

The fast infiltration rates of the dry Ontonagon soil trial (On-12) reflected the very porous surface layers present on all machine treatments (Fig. 5-19). Because of the unrestrained swelling phenomenon discussed earlier, water which passed through these surfaces encountered underlying soil which was much more porous than it ordinarily would have been. Inadequate seals between soil pedestals and rings may have been the cause of some of the fastest rates, but another major factor was likely the variability in permeability of the underlying soil, as evidenced by widely spaced rates for the hand-exposed treatment replicates.

This natural soil variability in infiltration was also evident in the moist Ontonagon soil trial (On-20) results, where the number of hand-exposed replicates was increased (Fig. 5-20). Machine excavation produced no effect on mean infiltration rate. Wheel traffic did produce major reductions in infiltration rate in the four- and six-pass cases, and a lesser reduction in the two-pass case. Apparently, the moist clay aggregates in this trial were better able to resist deformation, and hence maintain some porosity against light wheel traffic, than any of the silty aggregates of the Plano soil trials. This theory is supported by pore size distribution and penetration resistance data.

Results for restored pedestal surfaces were generally slower than those for the original treatment surfaces -- sometimes much slower (Fig. 5-20). Though a few of these discrepancies can be explained by sidewall channeling in the initial trial, the most likely explanation is that soil clays were continuing to swell at a very slow rate -- too slow to be detected during infiltration -- even after the initial infiltration tests. The test pedestals were thus less porous after restoration, despite the removal of some or all of the compacted surfaces.

Although the infiltration data for this trial were apparently not equilibrium values, they do strongly suggest relative differences in the resistance to water flow of the surface layers of compacted and undisturbed soils.

Infiltration rates for four of the five field sites show decreases with increasing wheel traffic. This reduction in infiltration occurred in both soil textures when the soil was moist (near the plastic limit), and also in the dry Plano soil. Reductions of over 90% were common. During the dry Ontonagon soil excavation, the upper horizons were so dry that the bed floor was covered with a layer of loose dry aggregates of gravel-like size and consistence. This layer withstood the pressure of the rolling tractor tires, leaving very porous wheel tracks whose infiltration rates were as fast or faster than those of the natural soil. These results are in general agreement with those of the pore size distribution studies reported earlier.

In general, removal of 2 cm of compacted soil restored some infiltrative capacity on the silty Plano soil. Removal of 10 cm of soil provided better restoration, however, even this amount did not allow complete restoration where traffic had been heavy. Restoration results on the clayey Ontonagon soil were clouded by problems with clay swelling. Morphologic examination of Ontonagon test pedestals suggested that under long-term equilibrium conditions, the restoration techniques employed might have yielded relative improvements similar to those demonstrated on the Plano soil.

Although machine excavation appeared to produce moderate infiltration reductions in a few cases, these data are not sufficient to draw any firm conclusions. Since only one out of seven surfaces excavated with toothed backhoe buckets showed a reduced infiltration rate, while both test surfaces excavated by a smooth bucket showed reductions, bucket style may prove to be an important factor in determining compaction effects during excavation. More work is needed in this area.

Penetration Resistance

To help determine whether penetration resistance might be useful as a field indicator of soil compaction and of compaction susceptibility during absorption system construction, a pocket-sized penetrometer was employed. Results are given in Table 5-8.

Table 5-8. Average penetrometer results at four field trial sites.

Treatment	Plano soil trials P1-24	 P1-26	 P1-19	Ontonagon soil trial* On-20
	kg/cm^2			
Hand-exposed	2.18a**	1.14a	2.74a	3.60abc
Machine-excavated	2.38a	0.98a	2.66a	3.84abc
One pass	3.16b***			
Two passes	3.86c	2.15b	3.86b	2.96a
Three passes	2.81b***			
Four passes		1.84b	4.12b	3.82b
Six passes		2.16b	4.04b	3.98c

*Dry aggregates at site On-12 too hard to be measured.

**Results within any trial followed by same letter not significantly different at 95% level (0.05 level).

***These results significantly different at 93.7% level (0.063 level).

On the silty Plano soil, the penetrometer did a good job of distinguishing wheel track surfaces from non-track surfaces, but could not differentiate between different levels of wheel traffic, nor between hand-exposed and machine-excavated treatments. The instrument also seems to have correctly determined which soils were closest to the plastic limit. The smallest average readings were obtained from the wettest soil, and the highest readings were from the driest soil. While the wettest soil would be expected to suffer the greatest infiltration reduction (Lambe, 1958a,b), this was not the case during these Plano trials. All three moisture levels resulted in major reductions in infiltration with compaction, and some of the greatest reductions occurred on the driest site. This soil would have to be considerably drier to avoid appreciable infiltration reductions due to wheel traffic.

The penetrometer was able to differentiate between the different wheel traffic treatments on the moist Ontonagon soil, but was unable to tell those treatments from the hand-exposed or machine-excavated surfaces. No measurements were possible on the dry Ontonagon soil, as soil strength exceeded the range of scale values.

It appears that penetration resistance can be used to identify compacted layers in some soil conditions but not in others. The technique was not capable of identifying any of the excavation-smeared surfaces in this study.

Penetration resistance does show some promise in identifying compaction-susceptible soil conditions, although current methods of hand estimation of soil consistence are probably easier, cheaper, and at least as reliable.

SECTION 6

DESIGN AND OPERATION OF MODIFIED SOIL ABSORPTION SYSTEMS

LITERATURE REVIEW

Proper performance of an on-site wastewater system utilizing soil absorption for ultimate disposal of the liquid depends upon the ability of the soil to completely absorb and purify all the wastewater produced. Initially, the soil may have a high infiltration rate and is able to absorb a greater quantity of liquid than applied. However, with continued application of wastewater, a clogging mat usually develops at the infiltrative surface. Clogging is not synonomous with failure because flow through the mat will continue. In fact, some clogging is beneficial to enhance purification. Therefore, proper design requires that the wastewater loading never be allowed to exceed the infiltration rate of the clogged soil or that the extent of clogging be controlled to maintain the desired infiltration rate.

Introduction on Construction

Soil clogging is a complex phenomenon that is the result of many mechanisms that often act simultaneously. They can usually be grouped into physical, chemical and biological processes. Not all mechanisms are equally significant, however. In their review of the literature, McGauhey and Krone (1967) concluded that biological agents and their activities are the most important cause of soil clogging. This is supported by the work of many investigators (Allison, 1947; McCalla, 1945, 1946, 1950); others have also excluded the possibility that microbial cells alone cause clogging (Bendixen et al., 1950; Winneberger et al., 1960). Factors influencing the development and the intensity of soil clogging may be the pattern of the wastewater application, the loading rate and the wastewater quality.

Methods of Application

Septic tank effluents may be added to soil absorption areas as the wastes are generated or they may be retained and then pumped to the absorption area as a dose. Between doses the soil infiltrative surface is exposed to the air during short resting periods. Long periods of resting are possible if two absorption areas are available. Wastewaters are added by trickle or dosing to one system while the other system rests.

The Effect of Dosing and Resting--

Following the work of Bendixen et al. (1950), Winneberger et al. (1960), Jones and Taylor (1965), and Thomas et al. (1966), it has been generally thought that biological clogging could not predominate, provided the soil absorption system remained at least intermittently aerobic. Early laboratory work with lysimeters showed repeatedly that the infiltrative capacity of the soil was reduced more slowly when periods of ponding were interrupted with periods of aeration. These findings have motivated several working concepts in septic tank practice that are meant to confer greater longevity on the system, such as installation of vent pipes to facilitate reaeration of the soil after a wetting front has passed, use of aerobic treatment units, use of dosing systems for controlled effluent application, and periodic resting of absorption systems by the use of twin disposal systems.

Much of the information on soil clogging has been obtained from column studies designed to simulate a natural field clogging regime. Generally, the studies use lysimeters with air-tight walls, which create anaerobic conditions within the soil below the clogging mat. Walker et al. (1973) has shown that aerobic conditions exist under soil absorption systems located in sand. Thus, most of the previous research has neglected to acknowledge the impact of redox conditions in designing laboratory experiments to evaluate the dynamics of soil clogging.

Recent work has shown that clogging mechanisms in aerated and nonaerated columns can be quite different. Magdoff and Bouma (1974) and Magdoff et al. (1974) showed that clogging was not delayed in aerated sand columns. The resistance of the clogging mat in soil columns that were aerated by perforating the column sidewall were shown to more closely reproduce the resistances measured below four clogged absorption fields in sands (Magdoff and Bouma, 1974). Thus, some of the reported work studying the dynamics of soil clogging is of limited applicability in determining acceptable loading patterns.

To obtain the necessary information, column experiments were designed which included column aeration as a variable (Perry and Harris, 1975). In the aerated and nonaerated columns studied, substantially different mechanisms induced both clogging and the restoration of the infiltrative surface by resting. This has implications for the use of data and conclusions from nonaerated column experiments of field conditions in coarse-textured soils, where aeration below the clogging mat usually prevails. Nonaerated columns clogged more slowly than aerated columns but infiltration rate recovery during resting was more rapid in the aerated columns (Perry and Harris, 1975). Therefore, data from laboratory columns for recommending design and operational requirements of soil absorption fields must be extrapolated with care.

The aerated column studies indicate that effluent application regimes, characterized by alternating anaerobic-aerobic conditions on a short-term basis (dosing and short cycle alternating seepage systems), could reduce infiltration as an intense crust forms directly below the surface during the aerobic (resting) phase. Once clogged, restoration of the infiltrative surface by resting requires at least three to four weeks in sands. This appears to be sufficient time to decompose 30 to 35% of the organic carbon present in the mat and reestablish acceptable infiltration rates (Perry and Harris, 1975). This implies that dosing and resting frequencies must be selected with care to prevent excessive clogging. It is yet unknown what these frequencies should be.

Dosing and alternating system designs have been frequently used; however, their operation in the field has been little validated. Though it has been recognized that different types of columns lead to differences in clogging mat development, almost no field verification of subcrust environment has been made. A study offering field data of operating replicating systems with companion laboratory column study would help to fill this gap.

Influent Wastewater Characteristics--

To help preserve the infiltrative capacity of the soil, raw wastewater is subjected to some form of pretreatment prior to application to the soil. The pretreatment method typically utilized is a septic tank, whose primary function is to remove gross objects, settleable solids and floatable matter from the wastewater stream. If not removed, these constituents can cause rapid clogging of the soil (Weibel et al., 1954). The characteristics of typical septic tank effluent are delineated in Tables 6-1 and 6-2.

The impact of wastewater quality on soil absorption system operation has been the subject of several investigations recently (Winneberger, 1960; Laak, 1970; Daniel and Bouma, 1974; Baker, 1977). The major question addressed in these studies has been whether improved effluent quality can enhance the ability of the soil to absorb the applied wastewater. The studies to date have been conducted in the laboratory under somewhat artificial conditions, and the results obtained have been generally inconclusive. In granular soils, a higher-quality effluent appears to affect the degree of clogging and yield a less flow-restrictive clogging layer. In structured soils, a similar effect has not been found. Further investigation is necessary to adequately delineate the influence of wastewater quality on soil infiltration rates.

One strategy for enhancing the quality of the wastewater applied to the soil involves eliminating potential pollutants at the source. A method that can yield significant pollutant reduction involves removal of the toilet wastes from the household wastewater stream through use of an alternative toilet system (Small Scale Waste Management Project, 1978) (Table 6-3). One hypothesis suggests that a septic tank soil absorption system receiving the remaining household wastewaters (greywater) could be reduced considerably in size due to a higher infiltratibility of the greywater compared to typical wastewater. However, little data are available which delineate the efficacy of septic tank-soil absorption of greywater.

Table 6-1. Septic tank effluent quality (Small Scale Waste Management Project, 1978).

Parameter	Samples	Mean	Coefficient of variation	95% confidence level	Range
BOD_5, unfiltered (mg/L)	150	138	0.42	129-147	7-480
BOD_5, filtered (mg/L)	130	109	0.47	100-118	7-330
COD (mg/L)	152	327	0.33	310-344	25-780
Total solids (mg/L) †	12	1340	0.37	1030-1650	920-2310
Volatile solids (mg/L) †	12	260	0.34	200-310	120-410
Suspended solids (mg/L) ‡	148	49	0.16	44-54	10-695
Volatile suspended (mg/L) ‡	148	35	0.18	32-39	5-320
Total nitrogen (mg N/L)	99	45	0.40	41-49	9-125
Ammonia nitrogen (mg N/L)	108	31	0.46	28-34	0.1-91
Nitrate nitrogen (mg N/L)	114	0.4	6.7	0-0.9	0-74
Total phosphorus (mg P/L)	99	13	0.34	12-14	0.7-90
Ortho phosphorus (mg P/L)	89	11	0.36	10-12	3-20
Total coliforms ($\log_{10}$ No./L) †	14	7.0	0.08	6.7-7.3	6.3-7.9
Fecal coliforms ($\log_{10}$ No./L)	151	6.7	0.24	6.4-7.0	2.0-8.2
Fecal strep ($\log_{10}$ No./L)	155	4.6	1.0	3.9-5.3	2.0-7.6

† Results shown were derived from only one site instead of seven.

‡ Log normal distribution.

Table 6-2. Septic tank effluent quality - investigator comparison.

Parameter and statistics	Wisconsin[†]	Cincinnati[‡]	New York[§]	Toronto[¶]	Cincinnati[#]	Connecticut[††]
BOD_5 (mg/L)						
Mean (no. of samples)	138(150)	138(44)[‡‡]	140(51)	240(21)[§§]	93	120(50)
Coeff. of variation	0.42	0.35		0.06		0.48
95% conf. int.	129-147	--		210-280		100-130
Range	7-480	64-256		70-385		30-280
COD (mg/L)						
Mean (no. of samples)	327(152)				220	200(50)
Coeff. of variation	0.33					0.41
95% conf. int.	310-344					175-225
Range	25-780					71-360
Suspended solids (mg/L)						
Mean (no. of samples)	49(148)[§§]	155(55)[‡‡]	101(51)	95(18)[§§]	45	39(47)
Coeff. of variation	0.16	0.54		0.08		0.98
95% conf. int.	44-54	--		79-115		28-50
Range	10-695	43-485		48-340		8-270
Total nitrogen (mg/L)						
Mean (no. of samples)	45(99)		36(51)			
Coeff. of variation	0.40					
95% conf. int.	41-49					
Range	9-125					
Volume (m^3)						
Mean (no. of samples)	4.7(7)	2.6(10)	--	≃1.8	Not reported	4.0(1)
Range	3.5-7.6	1.7-7.8				

[†] Seven sites, 1972 to 1976 (SSWMP, 1978).

[‡] Ten tanks, 1947 to 1948 (Weibel, 1949).

[§] Nineteen sites, 1955 (Salvato, 1955).

[¶] Four sites, 1961 to 1966 (Bernhart, 1967).

[#] One site, 1969 (Thomas and Bendixen, 1969).

[††] One tank, 1972 (Laak, 1973).

[‡‡] Calculated from the average values from ten tanks, six series of tests.

[§§] Calculated on the basis of a log-normal distribution of data.

Table 6-3. Pollutant reductions afforded by removal of toilet wastes from residential waste stream (Small Scale Waste Management Project, 1978).

Pollutant	Percent reduction*	
	Mean	Range
BOD_5	37%	20 to 49%
Suspended solids	61%	36 to 77%
Nitrogen	82%	67 to 99%
Phosphorus	30%	14 to 42%
Pathogenic organisms	Significant	--

*In terms of mass/person/day in the raw wastewater for residences with typical water-using appliances except garbage disposals.

MATERIALS AND METHODS

The two major objectives of this phase of the investigation were:

(1) to evaluate the effect of method of effluent application on soil infiltration rates, and

(2) to evaluate the effect of in-house wastewater segregation on soil infiltration rates.

Two distinct methods of wastewater application were evaluated under the first objective: (a) Once-daily-uniform application versus conventional application (trickle flow), and (b) Alternating periods of waste application and resting versus continuous application. The second objective was evaluated by comparing greywater septic tank effluent to combined wastewater septic tank effluent, both applied conventionally.

Carefully controlled experimental designs and procedures were developed. These procedures assumed that (1) column studies have not proven adequate to establish the size of soil absorption fields; (2) establishment of loading rates on any soil group requires experiments using a variety of loading rates including those that cause failure; and (3) the same soil and wastewater resources should be used to investigate a particular management scheme so that variations in the study can be attributed to that management scheme. To this end, field studies were designed using extensively monitored soil absorption cells at three field sites where soil conditions were similar. Three wastewater loading rates were selected ranging from conventional loading to four times conventional values.

A major goal in each of these experiments was to monitor the effects of the operational strategies and application rates on the dynamics of soil field failure as measured by soil permeability and soil moisture regime. All cells were, therefore, monitored to evaluate infiltration rates, soil moisture potential (tensiometry) and cell ponding. The following sections characterize the sites that were employed, detail the experimental designs,and describe the design, installation and operation of the experimental soil absorption cells.

Experimental Design

To provide a soil infiltrative surface of constant surface area for each of the experimental conditions, impermeable barrier rings impressed into the soil infiltrative surface were chosen. Based on a discussion with Professor W. R. Gardner (formerly Soil Physicist, Department of Soil Science, University of Wisconsin-Madison) concerning the size of the soil absorption cells, and with consideration given to the volume of wastewater available from a trial household and that required for the experimental design, it was decided to use a single outer barrier, circular in shape, with a diameter of 0.9 m (3 ft).

An extensive search was made to identify the most suitable material and method of fabrication for the numerous cell barriers. Discussions with University of Wisconsin staff knowledgeable in wood science and metallurgy indicated that galvanized iron would be the most suitable. A local metal fabricator was located to construct 20 gauge (0.036 in, 0.014 cm) galvanized iron into 0.9 m (3 ft) diameter cylindrical sections 0.3 m (1 ft) long with a single seam, coated with pitch and close-riveted to make the cylinder watertight. Details regarding the components of the cell and the installation procedures utilized are presented in "Site Design, Installation and Operation" section of this report.

The experimental design for this study employed a total of 66 specially designed soil absorption cells. Following are the details of the experimental design utilized to study each of the design and operation strategies.

Once-daily-uniform Versus Conventional Application (Site 1)--

The experimental design for this phase of the study employed 18 soil absorption cells at Site 1. Septic tank effluent was applied at three application rates and two methods of application, with three replicates for each experimental condition. Effluent was applied at a design rate based on soil morphology and hydraulic conductivity characteristics, or 2 cm/day, as well as at two and four times this rate. The wastewater application methods included conventional (semi-continuous trickle flow) and once- daily-uniform application. To simulate conventional gravity application, the conventional application cells received an average of eight small intermittent applications of septic tank effluent per day (time of application dependent on wastewater generation), trickled onto the washed hardrock from a single point above the center of the soil cell infiltrative surface. The once-daily-uniform application cells received an average of only one dose of septic tank effluent per day distributed over the cell infiltrative surface via a mini-distribution network. The time of application and the actual daily loading to the cells depended totally upon the residence wastewater generation patterns. The experimental design for this study is summarized in Table 6-4.

Alternating Versus Continuous Operation (Site 2)--

The experimental design for this phase of the study included two operation schedules and three loading rates, with triplicate cells for each experimental condition. One set of nine cells was operated continuously as in a conventional system. Each of the cells in the second set of nine will be operated for six months, or until the soil moisture tension readings taken below the infiltrative surface indicate rapidly decreasing infiltration rates. At that point, the cell will be removed from operation for a period of about six months. After this resting period the cell will be reloaded. The average daily loading rates studied included the recommended rate based on soil morphology and hydraulic conductivity characteristics; soil analyses indicated this to be 2 cm/day. In addition, 4 cm/day and 8 cm/day loading rates were included. All cells received the designated daily loading in an average of eight small applications trickled onto the washed hardrock from a single point above the center of the soil cell infiltrative surface. The time of application and the actual daily loading depended upon home wastewater generation patterns.

Table 6-4. Uniform vs. conventional application soil absorption cell experimental design.

Cell no.	Average daily loading rate (cm/day)	Treatment Identification	Application method
1-3	2	1 C	Conventional
4-6	2	1 D	Once-daily-uniform
7-9	4	2 C	Conventional
10-12	4	2 D	Once-daily-uniform
13-15	8	4 C	Conventional
16-18	8	4 D	Once-daily-uniform

Two ancillary investigations were also carried out at this site. To estimate the contribution of sidewall infiltration to total soil absorption system infiltration, a series of three cells were installed without the impermeable sidewall barriers. These cells were loaded at 4 cm/day. To study the maintenance of a soil infiltrative surface by chemical versus biological means, three additional soil absorption cells have also been installed. These cells were identical in construction and monitoring apparatus to the other cells. Septic tank effluent was applied to each of these three cells as described previously at an average daily loading rate of 4 cm/day. When the alternating cells are shifted from a loading period to a resting period, these three cells will be treated with the chemical oxidant, hydrogen peroxide. After treatment the cells will be rested for three days and then reloaded. The effect of chemical oxidation as a maintenance technique will be compared to that of biological oxidation under resting conditions.

The experimental design for this phase of the study is summarized in Table 6-5.

Table 6-5. Alternating vs. continuous operation soil absorption cell experimental design.

Cell no.	Average daily loading rate (cm/day)	Treatment Identification	Operation schedule
1-3	8	4 C	Continuous
4-6	8	4 A	Alternating
7-9	4	2 C	Continuous
10-12	4	2 A	Alternating
13-15	2	1 C	Continuous
16-18	2	1 A	Alternating
19-21*	4	2 H	Continuous
22-24**	4	2 S	Continuous

*These cells were treated with hydrogen peroxide.
**These three cells were installed without barriers, i.e., natural soil served as sidewall.

Greywater Versus Combined Wastewater Application (Site 3)--

To directly compare greywater versus combined wastewater soil absorption, a site was established where both wastewater types could be generated and applied to the same soil, to eliminate any confounding influences from the wastewater quality and soil characteristics of two separate sites. At Site 3, the existing drainage network was altered so that toilet wastes and greywaters were transported in separate drainage lines to a chamber outside the home. In this chamber, the two waste streams were combined in the appropriate proportions to yield a greywater stream and a combined wastewater stream. Each of these wastewater streams was processed through a small septic tank of appropriate scale (approximately 940 L), with the effluent applied to the soil absorption cells.

The experimental design for this phase of the study included three application rates and two effluent types, as well as a set of tapwater controls. Septic tank effluent was applied at the recommended rate of 2 cm/day, as well as at 4 cm/day and 8 cm/day. All cells received eight intermittent applications per average day with variations subject to home wastewater generation patterns. Greywater septic tank effluent was applied to a total of nine cells as was the combined wastewater septic tank effluent. Carriage water was applied as a control to a total of six cells. The experimental design for this study is summarized in Table 6-6.

Site Characterization

Household Characterization--

A series of small soil absorption cells was established *in situ* at three residential dwellings located near Arlington, Wisconsin. These residences were selected for the study after a preliminary review of the characteristics of the residing families and their water use indicated their compatibility with the proposed experiment. Questionnaires identified the residence characteristics. Periodic readings were made from water meters installed at each site to identify the magnitude of the respective daily wastewater flows. The characteristics of the three study residences are presented in Table 6-7. The design and operation strategy investigated at each site is outlined in Table 6-8.

Table 6-6. Greywater vs. combined wastewater soil absorption cell experimental design.

Cell no.	Average daily loading rate (cm/day)	Treatment Identification	Effluent applied
3,6	2	1 TW	Tapwater
7-9	2	1 GW	Greywater STE
22-24	2	1 CW	Combined wastewater STE
2,5	4	2 TW	Tapwater
10-12	4	2 GW	Greywater STE
19-21	4	2 CW	Combined wastewater STE
1,4	8	4 TW	Tapwater
13-15	8	4 GW	Greywater STE
16-18	8	4 CW	Combined wastewater STE

Soil Characterization--

General morphology--The soils at each site were identified initially using detailed soil maps and later verified using a truck-mounted hydraulic soil probe and by inspecting profiles from soil bore holes. The soil profiles were sampled and examined morphologically according to the Soil Survey Manual (Soil Survey Staff, 1951) and Soil Taxonomy (Soil Survey Staff, 1975).

Table 6-7. Residence characteristics.

Characteristic	Study site 1	2	3
Occupants			
Adults	2	2	3
Children (Age)	2(2,9)	3(1,7,8)	1(1)
Floors	2	2	1
Toilets	1	1	1
Automatic clotheswasher	Yes	Yes	Yes
Automatic dishwasher	No	Yes	Yes
Garbage disposal	No	No	No
Water supply	Well	Well	Well
Wastewater disposal	STSAS*	STSAS*	STSAS*
Mean water use**	210 gpd	250 gpd	190 gpd

*STSAS = Septic tank soil absorption system.

**Based on multi-day water meter readings taken over a 60- to 90-day period.

Table 6-8. Design and operation strategy studied at each site.

Site Identification	Design and operation strategy under investigation
1	Once-daily-uniform application (dosing) versus conventional application.
2	Alternating periods of loading and resting versus continuous loading.
3	Application of greywater septic tank effluent versus combined wastewater septic tank effluent.

Biopores--After the sites were excavated for installation of the experimental soil absorption cells, each cell surface was prepared by hand and vacuumed free of loose materials. At this time, each cell's soil infiltrative surface was carefully photographed. This photographic record accurately depicted worm channels and other biopores which were expected to affect soil hydraulic properties. These transparent slides were examined under a light stereomicroscope in the laboratory to ocularly determine the biopore-size distribution and the influence of these pores on infiltration rate and other selected properties.

Soil hydraulic and other selected physical properties--Selected soil properties were identified according to the following procedures. Percolation tests were conducted in three separate test holes at each site according to the procedure described in the Wisconsin Administrative Code (Sec. H62.20). These tests were performed at the depth at which wastewater would be applied to the soil infiltrative surface. At this same depth, *in situ* hydraulic conductivity measurements were made using the crust test method (Bouma and Denning, 1972; Bouma et al., 1973, 1974). Two locations within the area of the proposed field study were evaluated in this manner at each of the three sites. Undisturbed soil cores were taken using stainless steel rings in a sampling assembly designed for use with the truck-mounted hydraulic soil probe. These samples, 7.6 cm in diameter and 5.8 cm high, were returned to the laboratory where hydraulic conductivity and moisture retention curves were determined using the one-step outflow method (Jaynes, 1978). Also, bulk densities were determined for these samples (Bouma et al., 1974). Particle size analysis was conducted on representative samples according to the method of Day (1965).

Site Design, Installation and Operation

Once-daily-uniform Versus Conventional Application (Site 1)--

A detailed description of the establishment of Site 1, where the design and operation strategy of once-daily-uniform versus conventional application was studied, follows. Plan views of this site are presented in Figures 6-1 and 6-2.

A backhoe was used to excavate a small bed area approximately 6.4 m (21 ft) wide and 11.9 m (39 ft) long to a depth of 0.70 m (2.3 ft) (Fig. 6-3). The eighteen soil absorption cells were then placed in the excavated area as shown in Figure 6-4. The interior soil surface of each cell was then leveled off and hand-picked to expose the natural soil surface (Figs. 6-5 and 6-6).

Monitoring equipment was then placed in the cell. Four tensiometers were placed in each cell, two in the cell center at 5 cm and 50 cm below the infiltrative surface, and two within the cell at the cell perimeter at similar depths (Figs. 6-7 and 6-8). Four tensiometers were also placed at similar depths at opposite corners of the excavated area to allow natural soil moisture conditions to be monitored. Thermistors were also placed below the soil infiltrative surface in a number of the cells to allow temperature measurements to be made. An observation port, 0.075 m (3 in) in diameter, was then carefully placed on the infiltrative surface near the

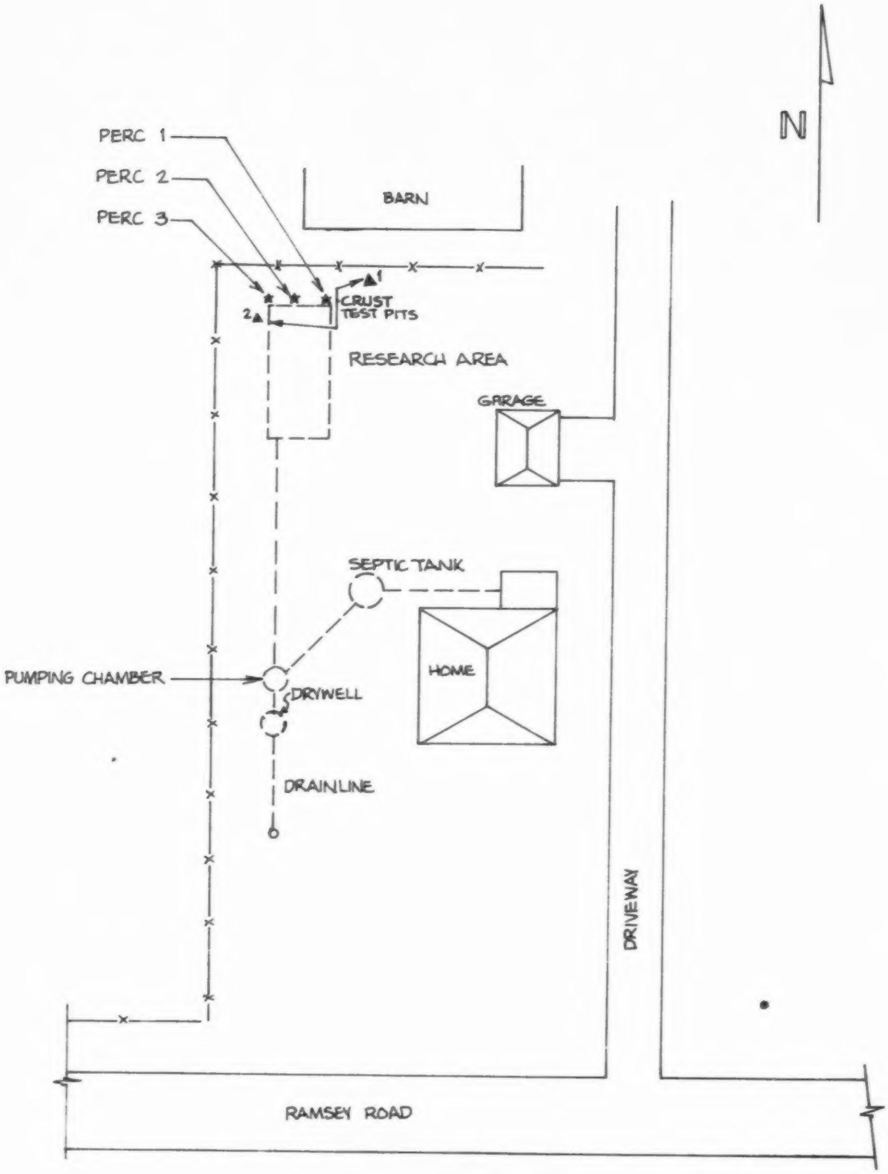

N
PERC 1
PERC 2
PERC 3
BARN
1
2
CRUST TEST PITS
RESEARCH AREA
GARAGE
SEPTIC TANK
HOME
PUMPING CHAMBER
DRYWELL
DRAINLINE
DRIVEWAY
RAMSEY ROAD

Figure 6-1. Plan view of Site 1 (approximate scale: 1 inch = 50 feet).

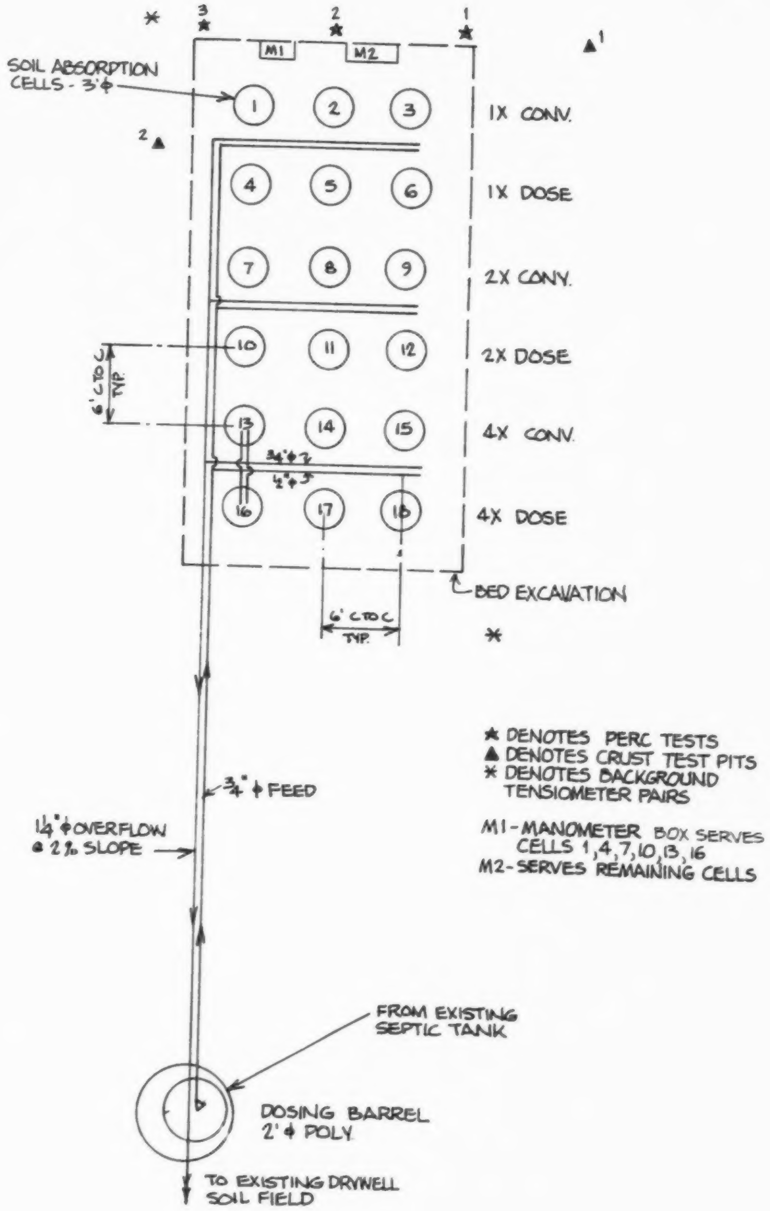

3
2
1
M1
M2
SOIL ABSORPTION CELLS - 3'ϕ
1
2
3
IX CONV.
4
5
6
IX DOSE
7
8
9
2X CONV.
10
11
12
2X DOSE
6' C TO C TYP.
13
14
15
4X CONV.
¾"ϕ
½"ϕ
16
17
18
4X DOSE
BED EXCAVATION
6' C TO C TYP.
★ DENOTES PERC TESTS
▲ DENOTES CRUST TEST PITS
✱ DENOTES BACKGROUND TENSIOMETER PAIRS
M1-MANOMETER BOX SERVES CELLS 1,4,7,10,13,16
M2-SERVES REMAINING CELLS
¾"ϕ FEED
1¼"ϕ OVERFLOW @ 2% SLOPE
FROM EXISTING SEPTIC TANK
DOSING BARREL 2'ϕ POLY
TO EXISTING DRYWELL SOIL FIELD

Figure 6-2. Plan view of research facilities - Site 1.

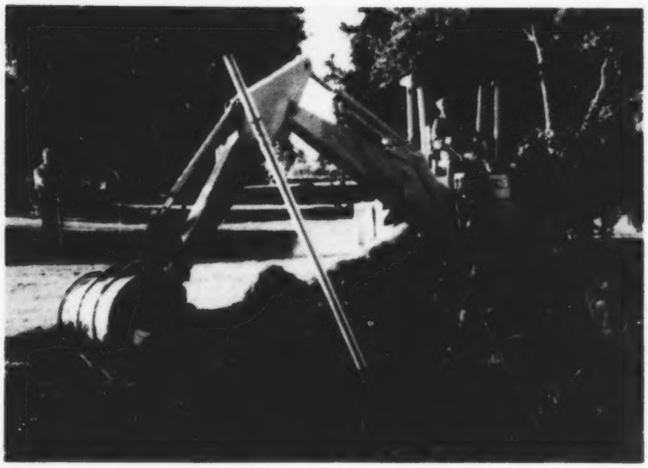


Figure 6-3. Soil abosorption cell area being excavated.

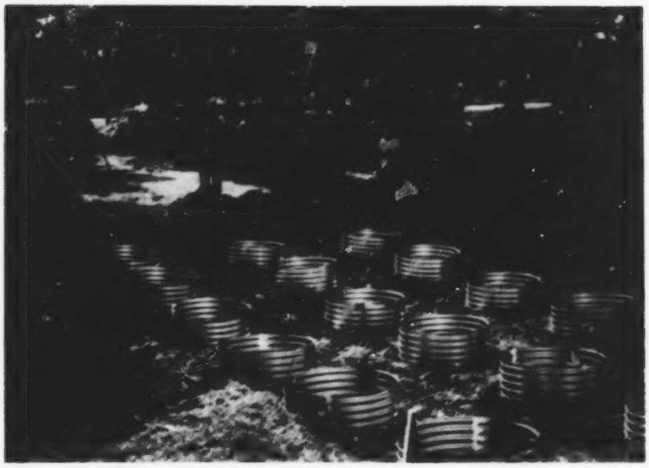


Figure 6-4. Soil absorption cell placement.

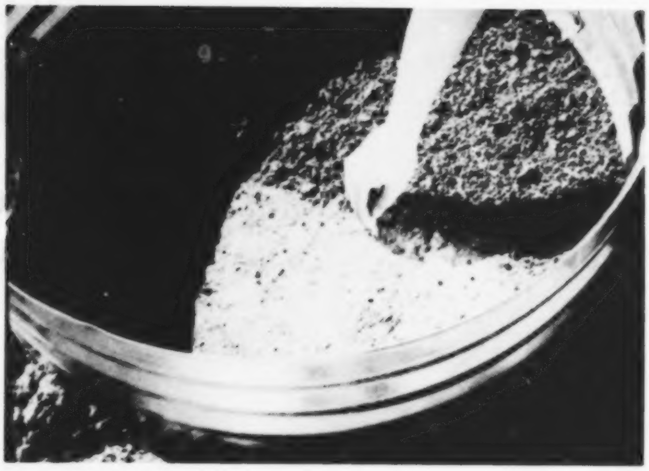


Figure 6-5. Soil cell infiltrative surface preparation.

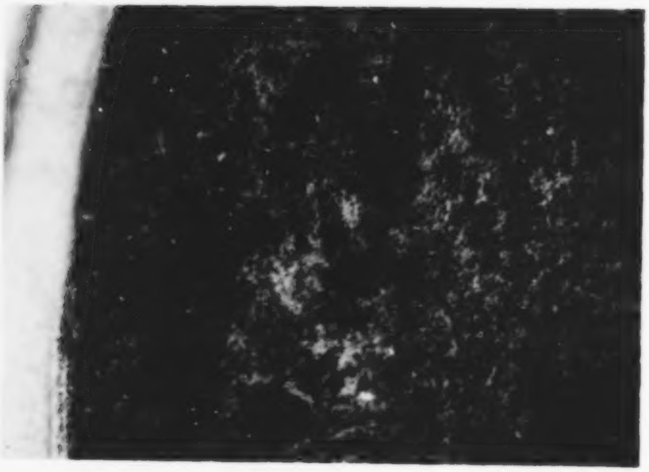


Figure 6-6. Typical natural soil structure of soil cell infiltrative surface after preparation.

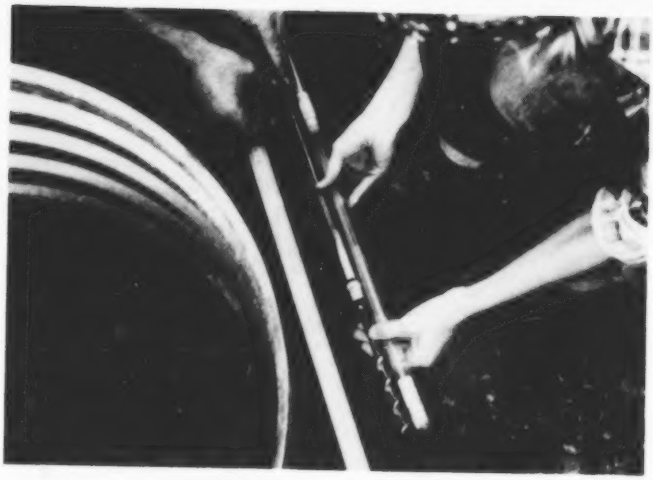


Figure 6-7. Soil tensiometers.

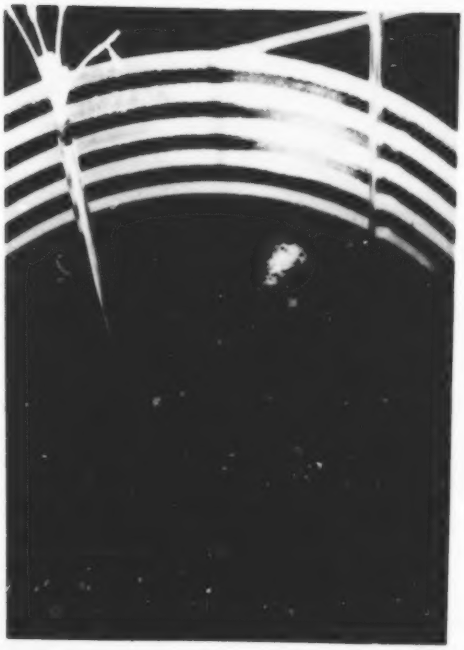


Figure 6-8. Soil tensiometers in place.

center of each cell. Additional details regarding the specifications for construction, maintenance and monitoring of these instruments are presented in the following section of this report. After placement of the monitoring devices, approximately 0.2 m (8 in) of 0.4 cm (1 in) washed hardrock was manually placed within the cell (Figs. 6-9 and 6-10).

Those cells receiving once-daily-uniform application of wastewater were outfitted with a mini-distribution system as shown in Figure 6-11. A piece of plastic pipe, 15.2 cm (6 in) diameter by 12.7 cm (4 in) long was placed vertically in each cell to allow connection/disconnection with the distribution systems and facilitate conventional trickle flow application at the cell center. All cells were then covered with approximately 8 cm (3.1 in) of the washed hardrock.

To facilitate monitoring, each of the 76 tensiometers was connected to one of two central tensiometer boards via a network of buried tensiometer tubing. To protect the tensiometry apparatus from freezing, heating tape was installed throughout.

A drainage fabric (Dupont Typar) was then placed over the gravel in each cell to prevent the downward movement of soil particles into the gravel, and to facilitate excavation into the cells if desired.

To provide a controlled loading of septic tank effluent to each cell, a specially designed application vessel was constructed for each cell. Each vessel had an inlet, overflow outlet and discharge outlet. The inlet was connected to a distribution network that delivered septic tank effluent to each of the 18 soil absorption cell vessels. The outflow outlet was connected to a drainage system that discharged to the existing household dry well. The invert of the outlet was set a certain distance above the vessel floor so that,when filled to overflow, the vessel would contain a known volume of septic tank effluent. In this way each of the 18 cell vessels applied the desired volume of wastewater, dependent on the application method and average daily loading rate (see Table 6-4). The discharge outlet was connected directly to a 1.2 cm (0.5 in) diameter electrically-operated solenoid valve.

Each vessel was set immediately on top of the drainage fabric covering the washed hardrock in the cells. In the case of the once-daily-uniform application cells, the discharge outlet from the application vessel was connected to the mini-distribution system. The discharge outlet from the vessel serving the conventional application cells directed the wastewater into the washed hardrock near the cell center.

To facilitate access to the application chamber as well as the observation ports, tensiometers and thermocouples in each cell, an access cylinder was placed vertically, extending from the top of the hardrock to 5 cm (2 in) above final ground surface. Each cylinder was equipped with an insulated, removable cover. Photographs showing the installation of the drainage fabric as well as the access cylinders and application vessels may be found in Figures 6-12 and 6-13.

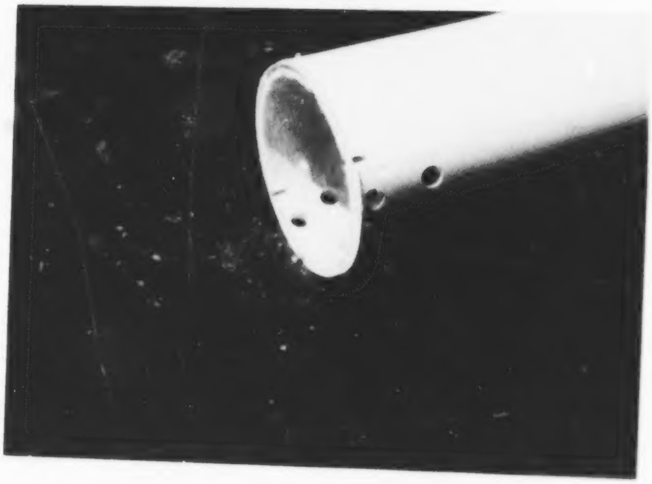


Figure 6-9. Observation port bottom detail.

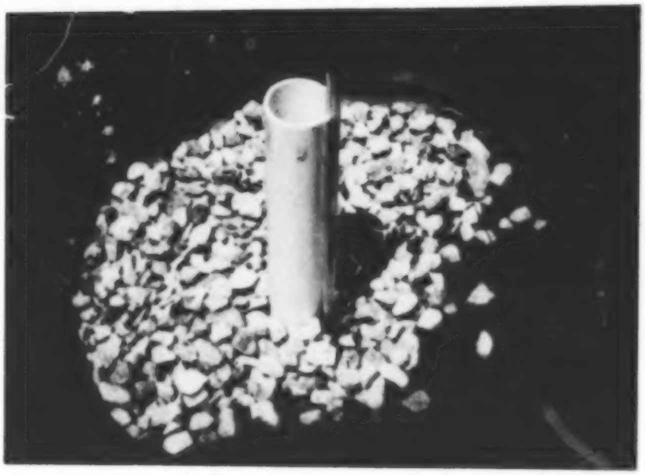


Figure 6-10. Tensiometers, observation port and gravel in place in cell.

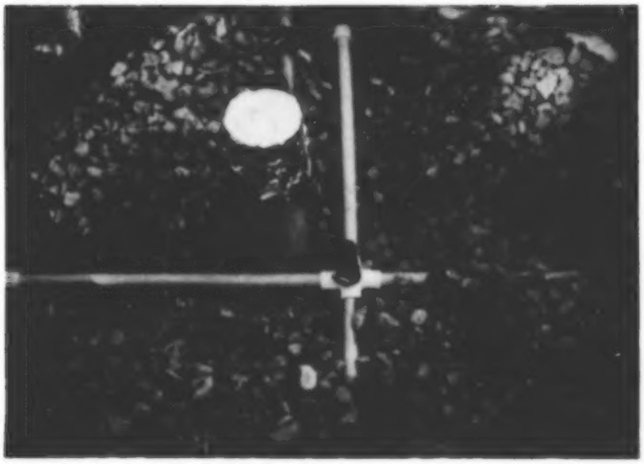


Figure 6-11. Mini-distribution network in place.

To obtain septic tank effluent for this experiment, the drain line connecting the existing household septic tank (4 m^3 or 1000 gal) and dry well was intercepted by a buried pumping chamber. This pumping chamber consisted of a section of corrugated culvert pipe, 1.2 m (4 ft) in diameter and 1.8 m (6 ft) long capped with an insulated removable cover and placed vertically. The line from the septic tank was directed into and through the chamber. Inside the chamber a basin 0.6 m (2 ft) in diameter and 1.2 m (4 ft) high was placed to receive the septic tank effluent (Fig. 6-14). A 1/2 hp effluent pump (Peabody Barnes, Model SE51) and a high and low-level float switch were located in the basin. Effluent was transported from this basin to the 18 soil absorption cells via a distribution network. Any overflow from the cell application vessels was discharged to the existing drywell via a drainage network (Fig. 6-15). The plumbing in the pumping chamber was established so that septic tank effluent could be bypassed directly to the drywell, or passed through the receiving tank and pumped to the drywell, or pumped to the soil cells.

Distribution of wastewater to each of the 18 soil absorption cells and application to the soil was controlled by a specially designed system (Fig. 6-16). A brief description of the operation of the system follows. After approximately 110 L (30 gal) of septic tank effluent flowed into the receiving basin in the pumping chamber, a high-level float switch was activated which in turn initiated a ten-minute cam-timer sequence. After approximately 18 seconds, the effluent pump was activated and discharged wastewater into the distribution system to the 18 cells. The pump continued to operate until a low-level switch was triggered, at which point it was deactivated. At this point, the application vessels to the nine conventional application cells were filled to the invert of the overflow outlet. The application chambers to the nine once-daily-uniform application cells were filled to approximately 1/8 of the level of the overflow outlet. Approximately 210 seconds into the cam-timer cycle, the discharge valves in the conventional application cells were opened to allow the wastewater to drain onto the washed hardrock and the soil infiltrative surface (the discharge valves serving the once-daily-uniform application cells were not opened each cycle, but rather only every eighth cycle). After application, the system was reset and ready for another cycle pending the accumulation of another 113 L (30 gal) in the pumping chamber. The system was designed to provide maximum control and flexibility in simulating both conventional (semi-continuous trickle flow) and once-daily-uniform application of septic tank effluent to a soil infiltrative surface.

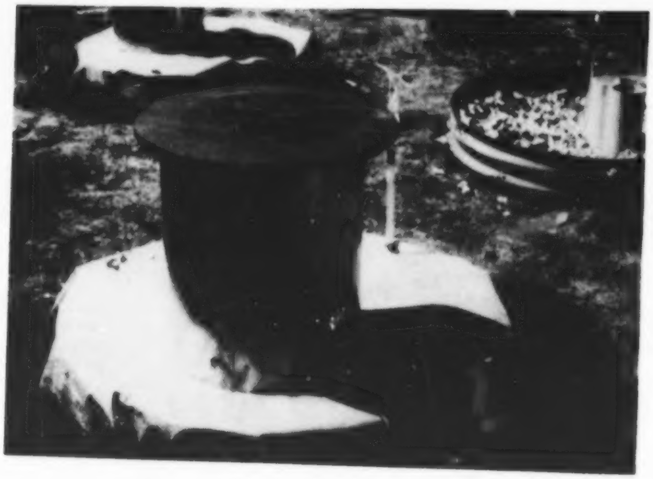


Figure 6-12. Placement of drainage fabric and access cylinders.

Figure 6-13. Application vessels and monitoring apparatus inside access cylinder.

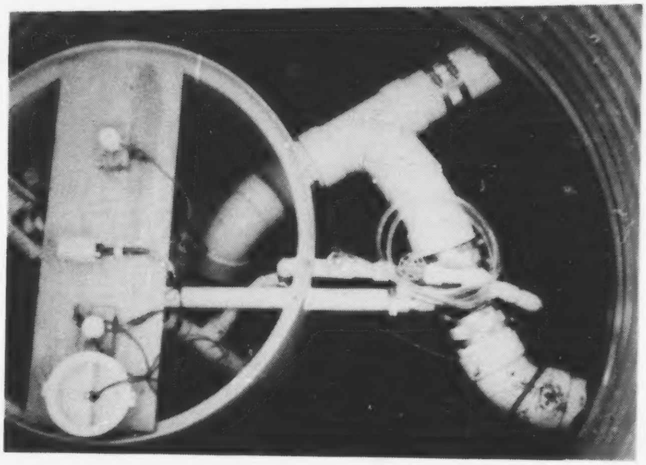


Figure 6-14. Pumping chamber.

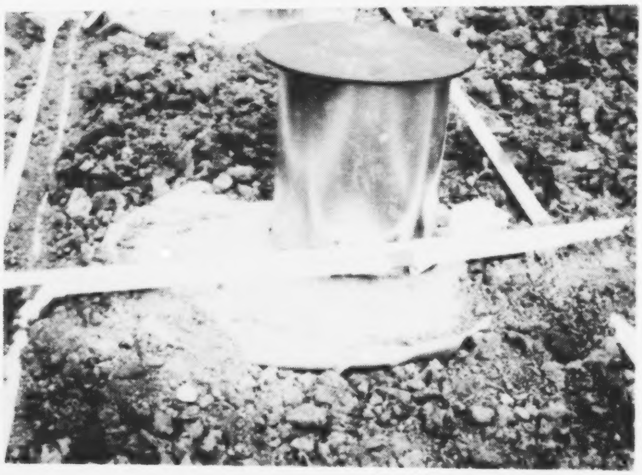


Figure 6-15. Soil cell distribution/drainage networks.

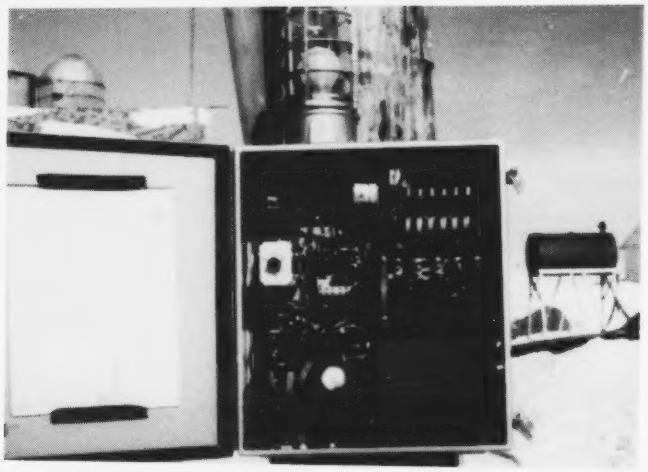


Figure 6-16. Uniform vs. conventional experiment control system.

A continuous chart event-recorder (Cole-Parmer, Model No. 8364-30) was included as part of the control system to provide a continuous record of wastewater application to the cells versus time of day. Additionally, two electrical event counters were included in the circuitry to record the same data.

Establishment of Site 1 was completed in December 1978. A photograph of the site after establishment was complete is shown in Figure 6-17.

Alternating Versus Continuous Operation (Site 2)--

The establishment of Site 2 was accomplished essentially as described for Site 1. This section briefly describes the installation and highlights any differences from Site 1. Plan views of the site are presented in Figures 6-18 and 6-19.

A backhoe was used to excavate a bed approximately 15.5 m (51 ft) long and 6.4 m (21 ft) wide to a depth of 0.70 m (2.3 ft). Twenty-one soil absorption cells were established as for Site 1. An additional three cells without impermeable barriers were manually excavated to yield a bottom infiltrative surface similar in area and configuration to the cells with barriers. The excavated bottom and sidewall infiltrative surfaces were prepared by hand as described previously. A photograph of the cell area during installation is shown in Figure 6-20. The cells utilizing sidewall infiltration are illustrated in Figure 6-21.

Monitoring equipment was installed in each cell as for Site 1, including four tensiometers, an observation port, and thermistors (in selected cells). In addition, sampling ports were installed in one cell in each set of triplicates to allow samples of soil air to be taken at 30 and 60 cm below the soil infiltrative surface.

Collection of septic tank effluent and distribution to the 24 soil absorption cells was accomplished as described for Site 1 (Fig. 6-22).

Distribution of the septic tank effluent to each of the 24 cells and application to the soil was controlled by a specially designed system similar to that used for Site 1. After approximately 102 L (27 gal) of septic tank effluent flowed into the receiving basin in the pumping chamber, a high-level float switch was activated which in turn initiated a six-minute cam-timer sequence. After approximately 18 seconds, the effluent pump began to discharge wastewater into the distribution system to the 24 cells. The pump operated until a low-level float switch deactivated it. At that point, the application vessel for each cell was filled to the invert of the overflow outlet. Approximately 144 seconds into the cycle, the discharge valves on all these vessels were opened, allowing the effluent to drain onto the washed hardrock at the cell center. After six minutes, the cam-timer cycle was completed and the system reset for another cycle pending the accumulation of another 102 L (27 gal) of septic tank effluent in the pumping chamber.

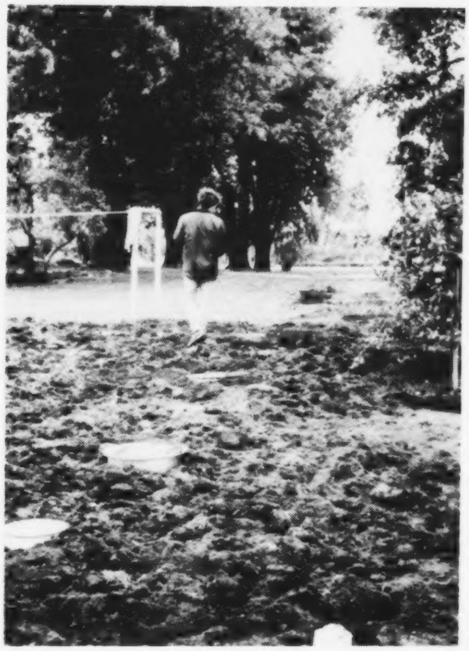


Figure 6-17. Site 1 after completion of installation.

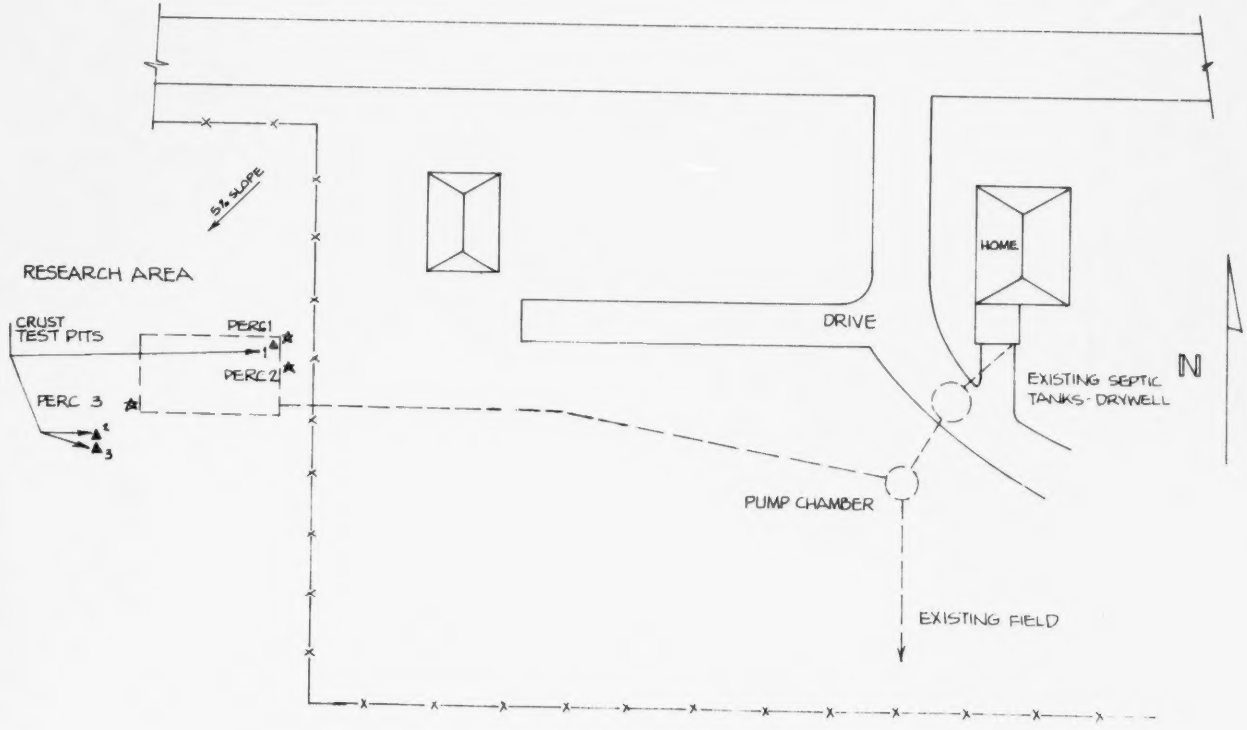

5% SLOPE
RESEARCH AREA
CRUST
TEST PITS
PERC1
PERC2
PERC 3
1
2
3
DRIVE
HOME
EXISTING SEPTIC
TANKS - DRYWELL
N
PUMP CHAMBER
EXISTING FIELD

Figure 6-18. Plan view of Site 2 (approximate scale: 1 inch = 50 feet).

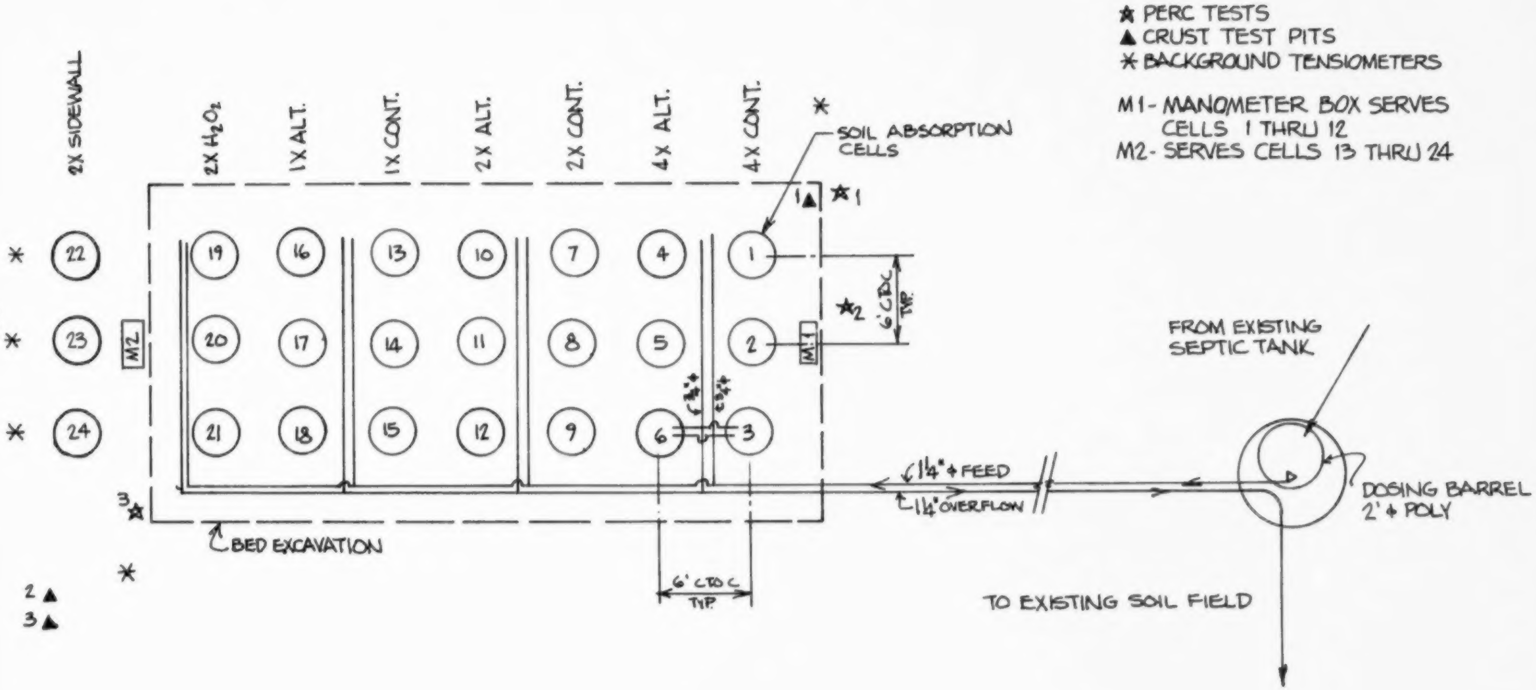

★ PERC TESTS
▲ CRUST TEST PITS
✳ BACKGROUND TENSIOMETERS
M1- MANOMETER BOX SERVES CELLS 1 THRU 12
M2- SERVES CELLS 13 THRU 24
2X SIDEWALL
2X H_2O_2
1X ALT.
1X CONT.
2X ALT.
2X CONT.
4X ALT.
4X CONT.
SOIL ABSORPTION CELLS
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
M1
M2
6' C TO C TYP.
6' C TO C TYP.
BED EXCAVATION
1¼" ⌀ FEED
1¼" OVERFLOW
¾" ⌀
FROM EXISTING SEPTIC TANK
DOSING BARREL 2' ⌀ POLY
TO EXISTING SOIL FIELD

Figure 6-19. Plan view of research facilities - Site 2.

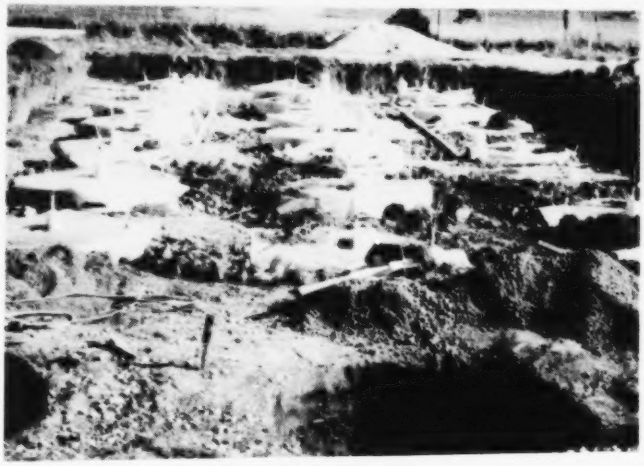


Figure 6-20. Site 2 during cell establishment.

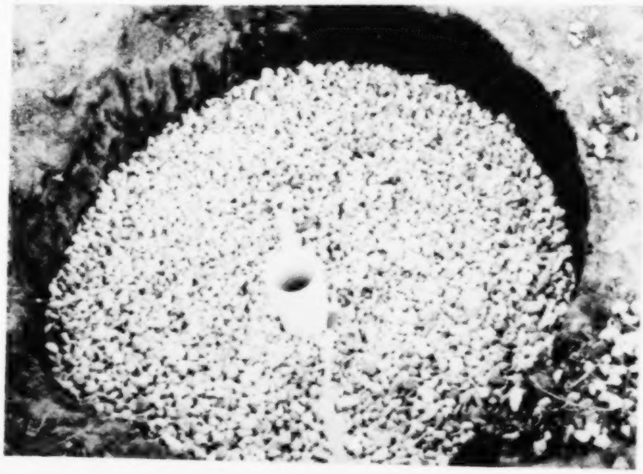


Figure 6-21. Soil absorption cell installation with no sidewall barriers.

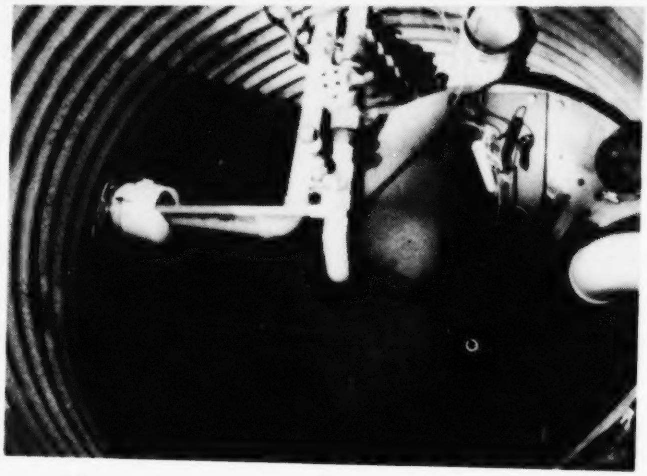


Figure 6-22. Septic tank effluent pumping chamber at Site 2.

Figure 6-23. Site 2 after completion of installation.

A continuous chart event-recorder (Cole-Parmer, Model No. 8364-30) was included in the control system to provide a continuous record of effluent application versus time of day. An electrical event counter was also included to record each application to the cells.

Establishment of the site was completed in August 1979. A photograph of the completed site is presented in Figure 6-23.

Greywater Versus Combined Wastewater Application (Site 3)--

The establishment of Site 3 was accomplished essentially as described for the other two sites. This section briefly describes the installation and highlights any differences. Plan views of the site are presented in Figures 6-24 and 6-25.

A backhoe was used to excavate a bed approximately 15.5 m (51 ft) long and 6.4 m (21 ft) wide to a depth of 0.70 m (2.3 ft). Twenty-four soil absorption cells were established as for Sites 1 and 2. A photograph of the cell area during installation is shown in Figure 6-26.

Monitoring equipment was installed in each cell as for Sites 1 and 2, including four tensiometers, an observation port and thermocouples (in selected cells). Additionally, gas sampling ports were installed in one cell in each set of triplicates receiving greywater and combined wastewater and in the two cells receiving tapwater at the 4 cm/day loading rate. These ports allow samples of soil air to be taken at 30 and 60 cm depths below the soil infiltrative surface.

Provisions for septic tank effluent and carriage water for application to the soil cells had to be accomplished differently than for Sites 1 and 2. This consisted of plumbing alteration in the home and the installation of a raw waste combination chamber, two small septic tanks and a pumping chamber. The existing drainage network inside the residence had to be altered so that greywater and toilet wastes were transported in completely separate lines. As a result, a new network was installed to transport the greywater from the kitchen sink, bathroom sink, bath/shower, clothes washer and water softener. The wastes from a conventional water carriage toilet were transported in the existing drain line. Both these wastewater streams were transported in 10 cm (4 in) diameter plastic pipe to a chamber located outside the home. This chamber consisted of a section of corrugated culvert pipe, 1.2 m (4 ft) in diameter and 1.8 m (6 ft) long, placed vertically in the ground and capped with an insulated removable cover. Inside the chamber, each waste stream entered its own small polyethylene basin, 0.46 m (1.5 ft) in diameter and 0.82 m (2.7 ft) high. In the grey-water basin, after approximately 9.8 gallons of wastewater accumulated, a small submersible sump pump (Peabody-Barnes, 1/3 hp, Model SSC26) operated by a float switch discharged the contents. A portion of the contents was directed to a greywater septic tank and another portion to a combined wastewater septic tank. In the toilet waste basin, after

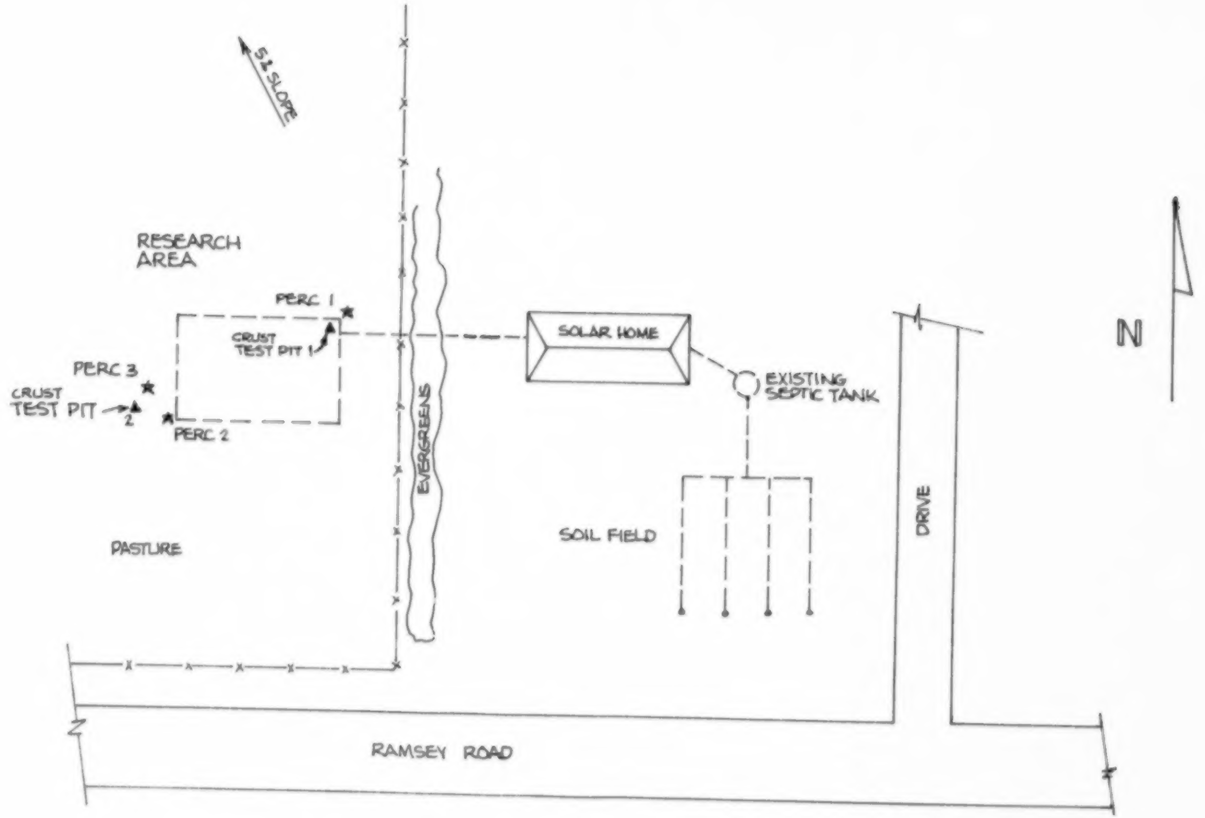

5% SLOPE
RESEARCH AREA
PERC 1
CRUST TEST PIT 1
PERC 3
CRUST TEST PIT 2
PERC 2
EVERGREENS
SOLAR HOME
EXISTING SEPTIC TANK
N
SOIL FIELD
DRIVE
PASTURE
RAMSEY ROAD

Figure 6-24. Plan view of Site 3 (approsimate scale: 1 inch = 50 feet).

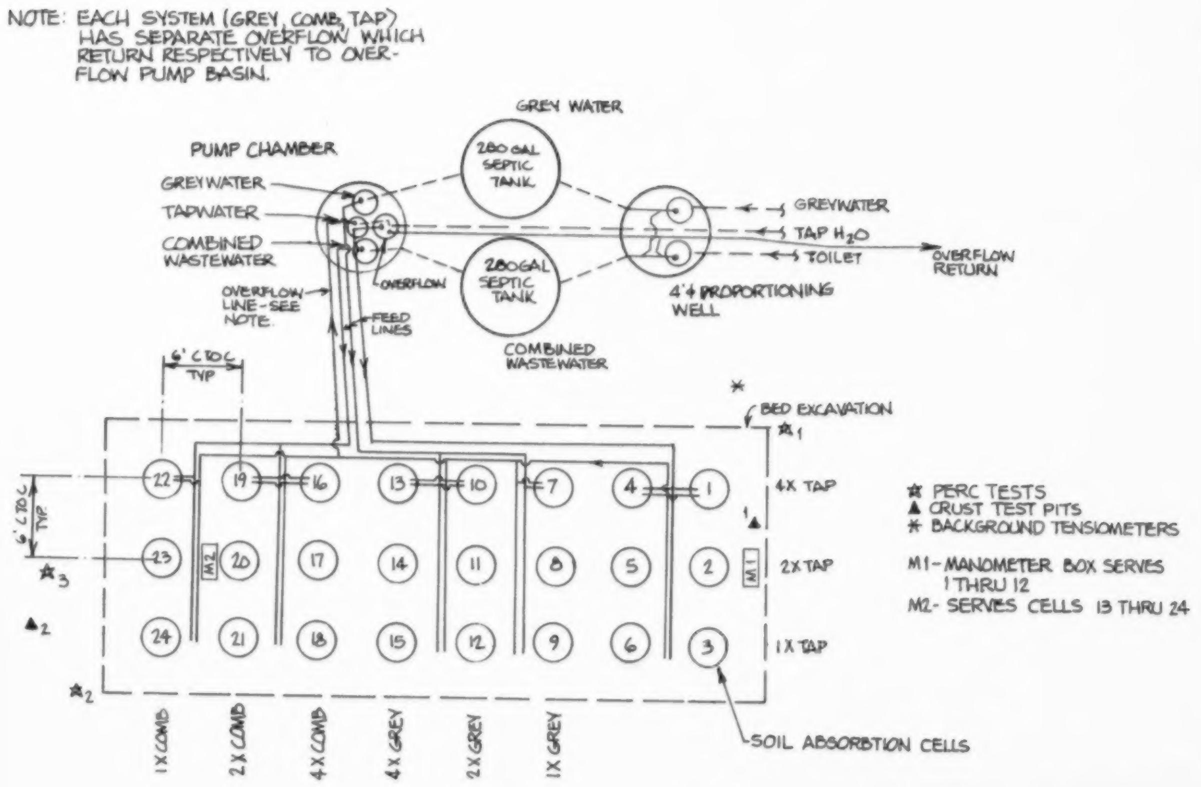

NOTE: EACH SYSTEM (GREY, COMB, TAP) HAS SEPARATE OVERFLOW WHICH RETURN RESPECTIVELY TO OVER-FLOW PUMP BASIN.
GREY WATER
PUMP CHAMBER
GREYWATER
TAPWATER
COMBINED WASTEWATER
280 GAL SEPTIC TANK
280 GAL SEPTIC TANK
OVERFLOW
GREYWATER
TAP H_2O
TOILET
OVERFLOW RETURN
OVERFLOW LINE-SEE NOTE.
FEED LINES
4'⌀ PROPORTIONING WELL
COMBINED WASTEWATER
6' C TO C TYP
BED EXCAVATION
22
19
16
13
10
7
4
1
23
20
17
14
11
8
5
2
24
21
18
15
12
9
6
3
M2
M1
4X TAP
2X TAP
1X TAP
★ PERC TESTS
▲ CRUST TEST PITS
* BACKGROUND TENSIOMETERS
M1- MANOMETER BOX SERVES 1 THRU 12
M2- SERVES CELLS 13 THRU 24
1X COMB
2X COMB
4X COMB
4X GREY
2X GREY
1X GREY
SOIL ABSORBTION CELLS

Figure 6-25. Plan view of research facilities - Site 3.

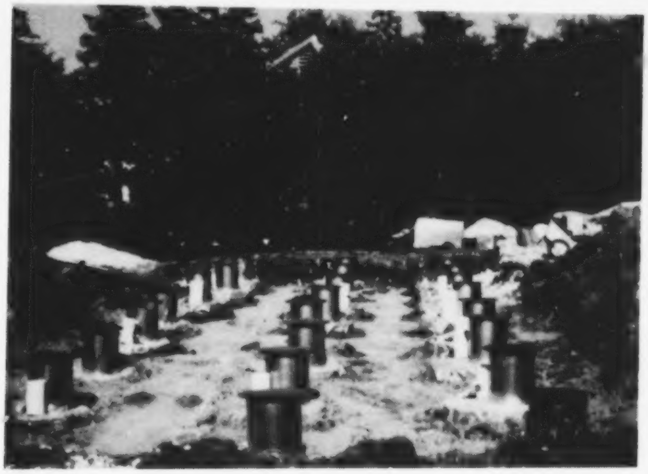


Figure 6-26. Site 3 during cell establishment.

approximately 6.3 gallons of wastewater accumulated, an effluent pump (Peabody-Barnes, 1/2 hp, Model SE-51) operated by a float switch discharged the contents. This pump, capable of handling 5 cm (2 in) diameter solids, directed a portion of the contents to the combined wastewater septic tank and the remainder to a sewer line connected to the existing home septic tank/soil absorption system. Both basins discharged through plastic pipe with a gate valve in each line to enable adjustment of the proportions of greywater and toilet water added to the combined wastewater septic tank. A photograph illustrating this combination well is presented in Figure 6-27.

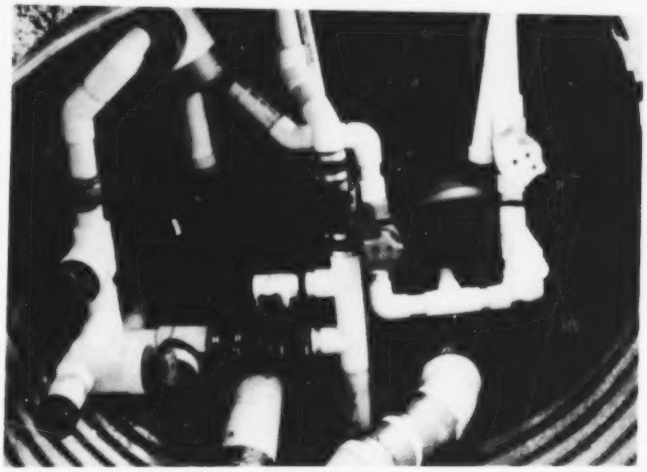


Figure 6-27. Raw waste combination well.

Two scaled-down septic tanks were installed to treat each of the raw waste streams. These tanks were fabricated from concrete manholes with an inside diameter of 1.22 m (4 ft) and a water depth of 0.91 m (3 ft) yielding a liquid volume of 1058 L (280 gal). This tank size was selected since it was predicted to yield a liquid detention time of about five days and provide a liquid depth of 0.91 m (3 ft), both of which were within the range typical of conventional full-size septic tanks. The inlets and outlets from each tank were baffled using a tee with the top end open and the bottom end submerged, 15.2 cm (6 in) on the inlet and 22.9 cm (9 in) on the outlet. The elevation difference between inlet to outlet was a drop of approximately 5 cm (2 in). A manhole cover, 0.61 m (2 ft) in diameter, was provided over the center of each septic tank installed approximately 7.5 cm (3 in) above final grade. Installation of these septic tanks is presented in Figure 6-28.

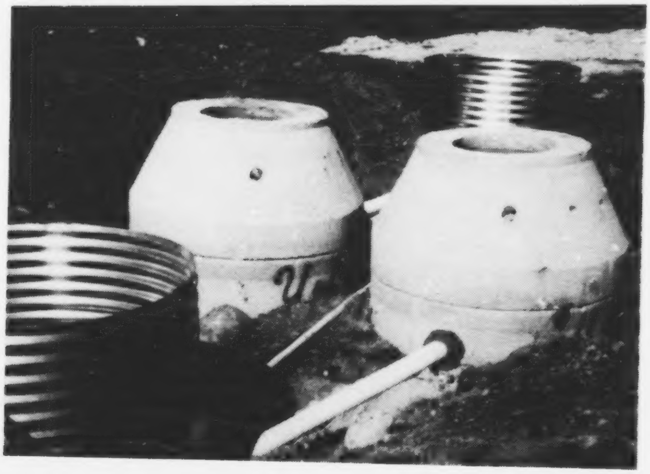


Figure 6-28. Installation of septic tanks.

The effluent from each of the two septic tanks flowed into a small pump basin located in a buried chamber. This chamber consisted of a section of corrugated culvert pipe, 1.37 m (4.5 ft) in diameter and 1.8 m (6 ft) long, placed vertically in the ground and capped with an insulated removable cover. Inside the chamber, each effluent stream entered its own small polyethylene basin, 0.46 m (1.5 ft) in diameter and 0.81 m (2.67 ft) high. Also located in this chamber were two other small polyethylene basins. One basin, 0.46 m in diameter and 0.81 m high, was periodically filled with tapwater from a cold waterline located within the home. Each of the three basins described so far also contained a submersible sump pump (Peabody-Barnes, Model SSC 26) and high- and low-level float switches. The effluent from each basin was distributed to the appropriate soil cells in three separate distribution/drainage networks. The fourth basin in the chamber was 0.46 m in diameter and 0.81 m high and was used to collect any overflow from the greywater STE basin, combined wastewater STE basin and the tapwater basin. This overflow basin contained a submersible sump pump (Peabody-Barnes, Model SSC 26) controlled by a float switch that periodically discharged the contents of the basin into the sewer line connected to the existing home septic tank/soil absorption field. A photograph of this pumping chamber is shown in Figure 6-29.

Distribution and application of the two effluents and the tapwater to the appropriate soil cells was provided by a specially designed control system. A brief description of its operation follows. When approximately 32.5 L (8.6 gal) of septic tank effluent accumulated in each of the two effluent basins, respectively, the high-level float switch in each basin was activated. Any further flow to a basin overflowed into the overflow basin. The tapwater basin was kept filled to its overflow level with its high-level float switch closed automatically except during application to the soil cells (more discussion follows). When all three high-level float. switches were activated, an application cycle was initiated. A six-minute cam timer was the prime controller. After approximately 24 seconds, tapwater was distributed to each of the tapwater cells until a low-level float switch was opened and deactivated the tapwater pump. Similarly, after approximately 86 and 173 seconds, greywater effluent and then combined wastewater effluent were distributed to the appropriate cells. At that point,

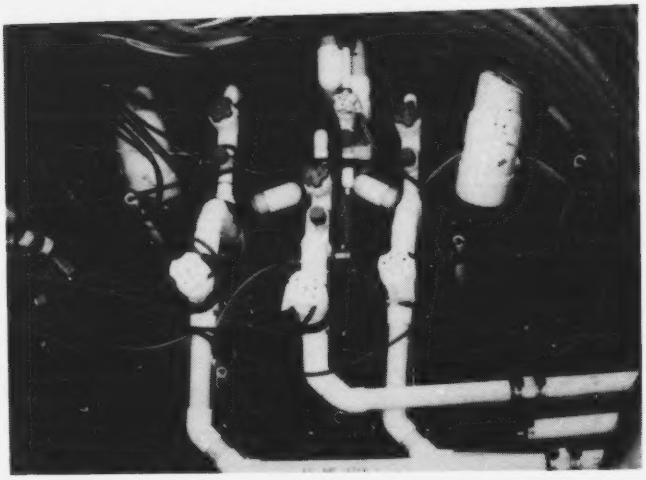


Figure 6-29. Pumping chamber at Site 3.

the application chambers in each cell were filled to the level of the overflow outlet yielding the proper volume of liquid. Approximately 252 seconds into the cycle, the discharge valves on all the cells were opened allowing the effluent to drain onto the washed hardrock at the center of the soil cell. At approximately the same time that the discharge valves opened, a 1.2 cm (0.5 in) diameter solenoid valve on the tapwater line from the home was opened to refill the tapwater basin to the overflow level. At the end of six minutes the cam-timer cycle was completed and the system reset for another application pending the generation of the necessary volume of greywater and combined wastewater septic tank effluents.

A continuous chart event-recorder (Cole-Parmer, Model No. 8364-30) was included as part of the control system to provide a continuous record of greywater and toilet waste generation and application to the cells. Additionally, three electrical event-counters were included to record the same data.

Establishment of Site 3 was completed in September 1979. A photograph showing the site after installation is presented in Figure 6-30.

Figure 6-30 Site 3 after installation was completed.

Monitoring

Climatic Conditions--

The monitoring of general meteorological conditions, as recorded at the Arlington Experimental Farms Office, was assumed adequate for the scope of this study. All of the field experimental sites were within a three kilometer radius of this National Weather Service reporting station. Pertinent records of monthly data for precipitation and temperature were maintained. Special note was made of any climatic events significantly affecting the operation, instrumentation, and monitoring of the experiments.

Wastewater Characterization--

The wastewater effluents applied to the soil absorption cells at each site were characterized quantitatively and qualitatively as follows.

Quantitative characterization--The quantitative characteristics of the wastewater application to the soil cells were continuously monitored at each site. A continuous chart event-recorder (Cole-Parmer, Model No. 8364-30) recorded each application of wastewater to the soil cells versus time of day. Electrical event-counters tabulated the number of wastewater applications as well. These data, coupled with the known volume of wastewater per application to a given cell, were used to determine the average daily loading rates and representative hourly and daily loading patterns.

Qualitative characterization--Flow-composited samples (24-hour) of each septic tank effluent, as well as the tapwater control at Site 3, were periodically collected. To facilitate this sample collection, provision was made in the plumbing system as follows. A manually operated gate valve was installed as a branch in the discharge line from the sump pump. The outlet from this valve was connected to a section of 1 cm internal diameter (i.d.) Tygon tubing, which led to a polyethylene sample container (3.8 L) in a refrigerated cooler. To collect a composited sample, the gate valve was opened partially. Each time the sump pump operated during a wastewater application cycle, a small portion of the effluent was directed into the refrigerated sample container. After approximately 24 hours, the collected sample was transported to laboratories at the University of Wisconsin. Analyses were then performed for chemical/physical and microbiological parameters according to procedures outlined in Standard Methods (1976).

Soil Cell Monitoring--

Infiltrative properties--Bottom area infiltration rates for each cell were measured approximately bi-monthly using a constant-head, permeameter-type device. This device maintained a constant infinitesimal head at the infiltrative surface during measurement. After an equilibration period, the volume of water applied per unit time was measured. This procedure was repeated until a constant rate was determined. This technique conveniently and accurately reflected the infiltrative properties of the cells.

Soil moisture tension--Soil moisture conditions under each soil absorption cell were monitored with a network of tensiometers. Four tensiometers were placed in each cell, two in the cell center at 5 cm and 50 cm below the infiltrative surface, and two near the cell perimeter at similar depths. Figures 6-7 and 6-8 depict installation and location of the tensiometer pairs. Two additional sets of tensiometers, one at each end of each site, were placed at similar depths to monitor natural or background soil moisture conditions. Procedures for the measurement of soil moisture potential and related soil hydraulic parameters have been substantially treated elsewhere (Richards, 1965; Bouma et al., 1974; Bouma, 1975b).

The tensiometers were constructed of 22.2 mm (7/8 in) outside diameter (o.d.) clear acrylic tubing and 22.2 mm o.d. porous ceramic cups. The porous cups, obtained from Soil-Moisture Equipment Corporation, Santa Barbara, CA, have a wall thickness of 1.59 mm (1/16 in). These cups have a bubbling pressure or air entry value of greater than 1 bar (1000 mbar) and a water transmission rate of greater than 10 ml/cm^2/hr/bar of pressure difference across the cup ball. Soil moisture tensions measured in studies of this type generally do not exceed 500 mbar (Bouma et al., 1974a). More commonly, tensions of less than 200 mbar are encountered. Nylon tubing with 3.18 mm (1/8 in) o.d. was used as the lead conduit from the tensiometer cup to the mercury (Hg) manometer.

The tensiometer design used in the study is presented in Figure 6-31. As shown, two porous cup units were built into each tensiometer set, 45 cm apart for appropriate depth placement. The porous cups were machined for proper fit with the acrylic tube housing in the shops of the Department of Agricultural Engineering, University of Wisconsin-Madison. Each tensiometer set was tested after assembly to insure that each porous cup could hold a tension of at least 500 mbar Hg. The instruments were also checked for susceptibility to freezing damage. Each tensiometer was connected to a central Hg manometer and soil moisture tension reading board (graduated in mbar Hg). Two such central manometer units were located at each site (Fig. 6-23).

The manometer lead tubing connecting the tensiometers in each cell to the manometer box was paralleled by electrical resistance heating tape to protect these water-filled tubes from freezing in winter. The exposed tubing in the manometer boxes was protected from freezing by styrofoam insulation, heating tape, and incandescent light bulbs. The center tensiometer assembly and the flushing tubes for all tensiometers, located in each cell access compartment, were protected from exposure and freezing in a similar manner.

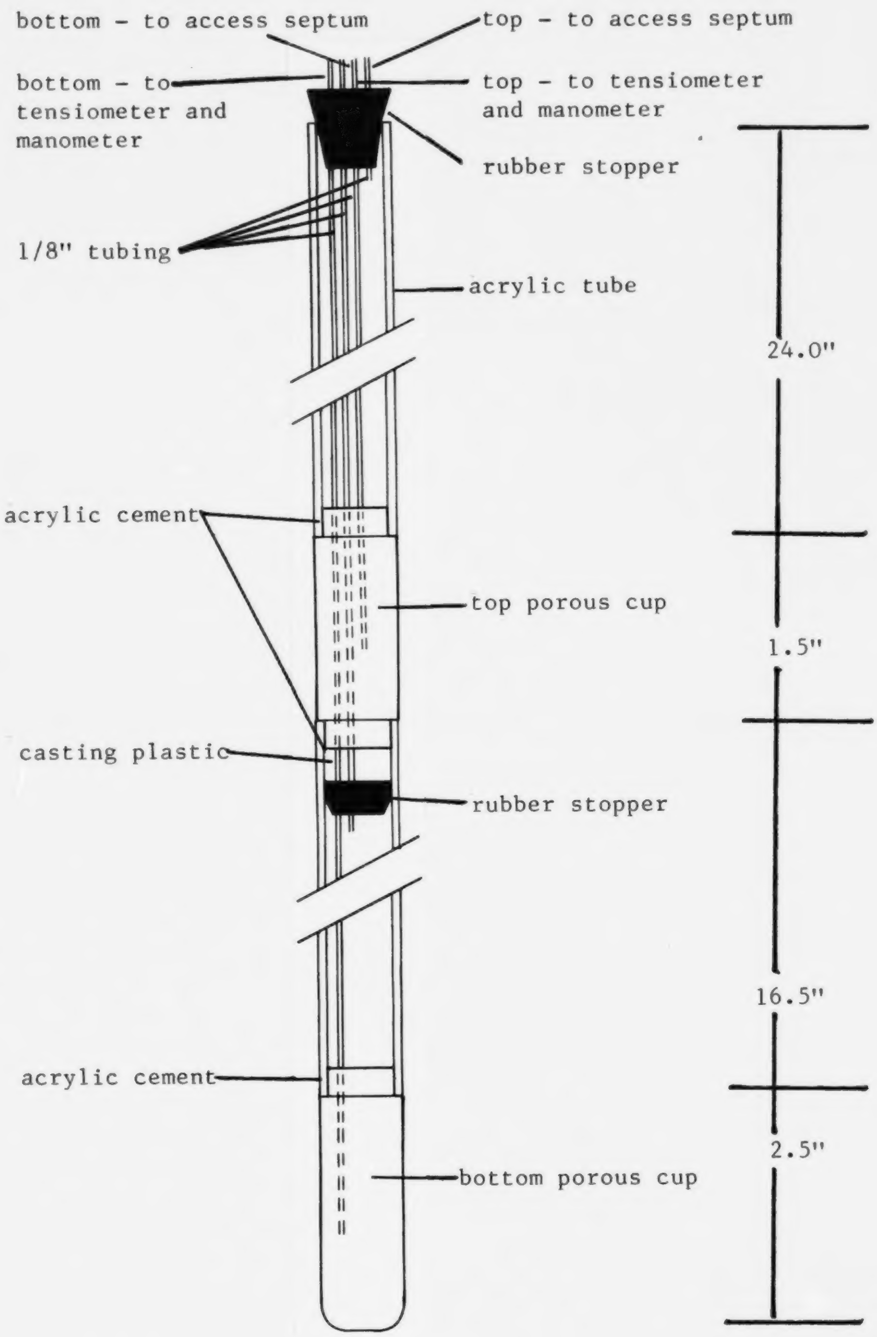

bottom - to access septum
top - to access septum
bottom - to tensiometer and manometer
top - to tensiometer and manometer
rubber stopper
1/8" tubing
acrylic tube
24.0"
acrylic cement
top porous cup
1.5"
casting plastic
rubber stopper
16.5"
acrylic cement
2.5"
bottom porous cup

Figure 6-31. Tensiometer design.

In the cell access compartment were service leads to each tensiometer. These 3.18 mm (1/8 in) o.d. leads, stoppered with rubber septa, provided convenient access to each tensiometer for back-flushing on an approximately monthly maintenance schedule. Routine servicing of tensiometers also included inspection of the accessible tensiometer air traps, inspection of nylon tubing for flaws or breaks at joints, replacement of defective septa, replacement of Hg where necessary, and repair of freeze-prevention systems. Tensiometer response data were collected weekly at all sites.

Observation wells--Effluent ponding above the infiltrative surface of each cell was monitored with observation wells. These wells were constructed from 0.08 m (3 in) o.d. PVC pipe. Each well was positioned with its bottom flush with the infiltrative surface, and with the upper end accessible through the access chamber of each cell. The wells were stoppered except during monitoring to keep out unwanted debris and fauna. Figure 6-10 shows the location of the observation well in the cell.

Each of these wells was inspected on an approximately weekly basis. Moisture conditions, measured depth of ponding, and other conditions observed in each well were recorded.

In December 1979, additional observation holes were augered to a depth of approximately 1.75 m at selected points in Sites 2 and 3. Observations of ponding in these auger-holes were made until freezing conditions precluded this activity. In the future, a network of piezometric wells will be installed at each of the sites to monitor water table mounding as influenced by treatments and rates. Other soil moisture measurement techniques will be implemented as needed to augment methods already in use.

Thermometric conditions--Soil temperature conditions were monitored in selected cells at each site electrical resistance thermocouples were placed at varying depths above and below the infiltrative surface and in the central manometer boxes for periodic temperature determinations. These thermocouples were constructed of copper-constantan thermocouple wire and connected to a Wescor TH-60 Potentiometric Thermometer for direct temperature readout. Readings were collected on an approximately weekly basis, as were ambient air temperature and temperature at various depths in selected cells.

Temperature readings taken for depths below the infiltrative surface aided in assessing the impact of the various rates, methods, and types of effluent application on soil physical, chemical, and microbiological conditions. Cell and manometer box temperatures were taken to monitor operational conditions of the tensiometry and dosing apparatus.

Data Handling and Analysis

Selected measurements were analyzed using the Statistical Analysis System (SAS) developed by Barr et al. (1978) and available through Administrative Data Processing, University of Wisconsin-Madison. Other data handling and computations were done manually using conventional statistical techniques.

RESULTS AND DISCUSSION

Soil Absorption Cell Experiments

Soil Properties--

Some general characteristics of the Plano silt loam soils found at each of the three Arlington field sites were discussed substantially in Section 4. Plano silt loam is a well-drained member of the fine-silty, mixed, mesic, Typic Argiudolls. The Plano soils typically have very dark brown friable silt loam A horizons, brown silty clay loam B2 horizons to a depth of about 45 inches, and IIB3 horizons of stratified silt loam, loam, clay loam, and sandy loam outwash or sandy loam till (SCS, 1973).

Characterization--Selected soil properties were determined in situ or in the laboratory for those soil horizons utilized in the subsurface disposal of septic tank effluent. In these experiments, the layer 70 cm (28 in) below the true ground surface was selected as the infiltrative surface. This depth corresponds roughly to that utilized in conventional waste disposal construction locally.

Particle size analysis--Morphological field investigations at each of the Arlington sites confirmed that the soil profiles fall within the range of characteristics of Plano silt loam, as previously described. More intensive sampling of the B22t horizon provided exact determinations of particle size distribution at each site. Multiple samples from each site yielded the mean sand, silt, and clay fractions presented in Table 6-9. As shown, the clay content at each site falls barely in the silty clay loam USDA textural class (> 40% clay constitutes a silty clay). Because of this heavy silty clay loam character, water movement characteristics may be significantly different from those in Plano soils with as little as 27% clay in the silty clay loam B22t horizon, such as those reported by SCS (1967).

Table 6-9. Particle size analysis - Arlington Plano soils [at the infiltrative surface - 71 cm (28 in) depth].

Site	Percent by weight			
	Sand (0.05-2.0 mm)	Silt (0.002-0.05 mm)	Clay (0.002 mm)	USDA texture)
1	8	52	40	silty clay loam
2	11	49	40	silty clay loam
3	9	51	40	silty clay loam

Percolation tests--Standardized percolation tests were conducted at each site in triplicate. The results ranged from 41 to 152 min/cm (16 to 60 min/in), as presented in Table 6-10. All individual test values for each site are within the range of acceptable values (Wisconsin Administrative Code, Sec. H62.20). The mean test values at all three sites are lower, i.e., faster, than expected for this soil. Percolation rates for Plano silt loam soils are reported as ranging from 114 to 152 min/cm by SCS (1978a,b). Also, since the B22t horizons of these Plano soils are on the extreme heavy end of silty clay loam, slower percolation rates might be expected here. These variations from predicted behavior may be at least partially explained by the number and size of biopores (e.g., worm channels) present in these soils (as discussed later). Variations among results at each site depend upon test-hole placement.

Table 6-10. Percolation test results - Arlington Plano soils.

Site identification	Pit identification	Rate, min/cm*	Site mean
1	1	68.6(27)	
1	2	68.6(27)	
1	3	40.6(16)	
			59.3(23.3)
2	1	71.1(28)	
2	2	152.4(60)	
2	3	63.5(25)	
			95.7(37.7)
3	1	104.1(41)	
3	2	55.9(22)	
3	3	55.9(22)	
			72.0(28.3)
Mean over all sites			75.6(29.8)
Standard deviation over all sites			33.5(13.2)
95% confidence interval over all sites			53.2-98.0(20.9-38.6)

*Parentheses indicate rate in min/in.

Hydraulic conductivity--Results of crust test determinations of hydraulic conductivity for each site are presented in Figure 6-32. At each site, hydraulic conductivity (K) decreased rapidly from a high near-saturation value as the soil moisture tension increased up to, and beyond, 20 mbar. Such conductivity relationships are expected, since the larger pores -- both structural and biotic -- with the greatest conductivities would no longer be transmitting fluids at these tensions. At least two crust tests were conducted at each site.

At Site 2, a third crust test was performed to attempt to evaluate the contribution of biopores to the conductivity measured. This test was carefully located to avoid as many biopores as possible. As shown in Figure 6-32, Site 2, a marked reduction in the near-saturation conductivity was measured.

The results of the hydraulic conductivity tests at all three field site locations are compiled in Figure 6-32. Presented in this fashion, the results show considerable variability. However, statistical analysis of the data (Jaynes, 1978) indicates that the variability is not significant and that the data can be grouped together. Mean hydraulic conductivity values as well as the upper and lower limits of the 95% confidence interval were calculated for the combined data as shown in Figure 6-33. These calculations were made assuming the simple empirical relationship between hydraulic conductivity, K, and soil moisture tension, as:

$$\log K = a \tau^{1/2} + b$$

where K = hydraulic conductivity; τ = soil moisture tension; and a and b are regression constants.

Moisture retention--Moisture retention determinations by the one-step outflow method are presented in Figure 6-33. Within the range of soil moisture tensions examined, considerable variability in volumetric water content exists between the sites. At Site 1 the moisture retention curve appears to level off at a somewhat higher water content than at the other two sites. This may be interpreted to indicate a higher percentage of smaller, moisture-retaining pore sizes in this soil moisture tension range exhibited by the curves of other sites. Much of the between-site variability in this soil moisture release measurement may be attributed to variation in particle size distribution, natural soil structure, and the frequency, size, and continuity of biopores.

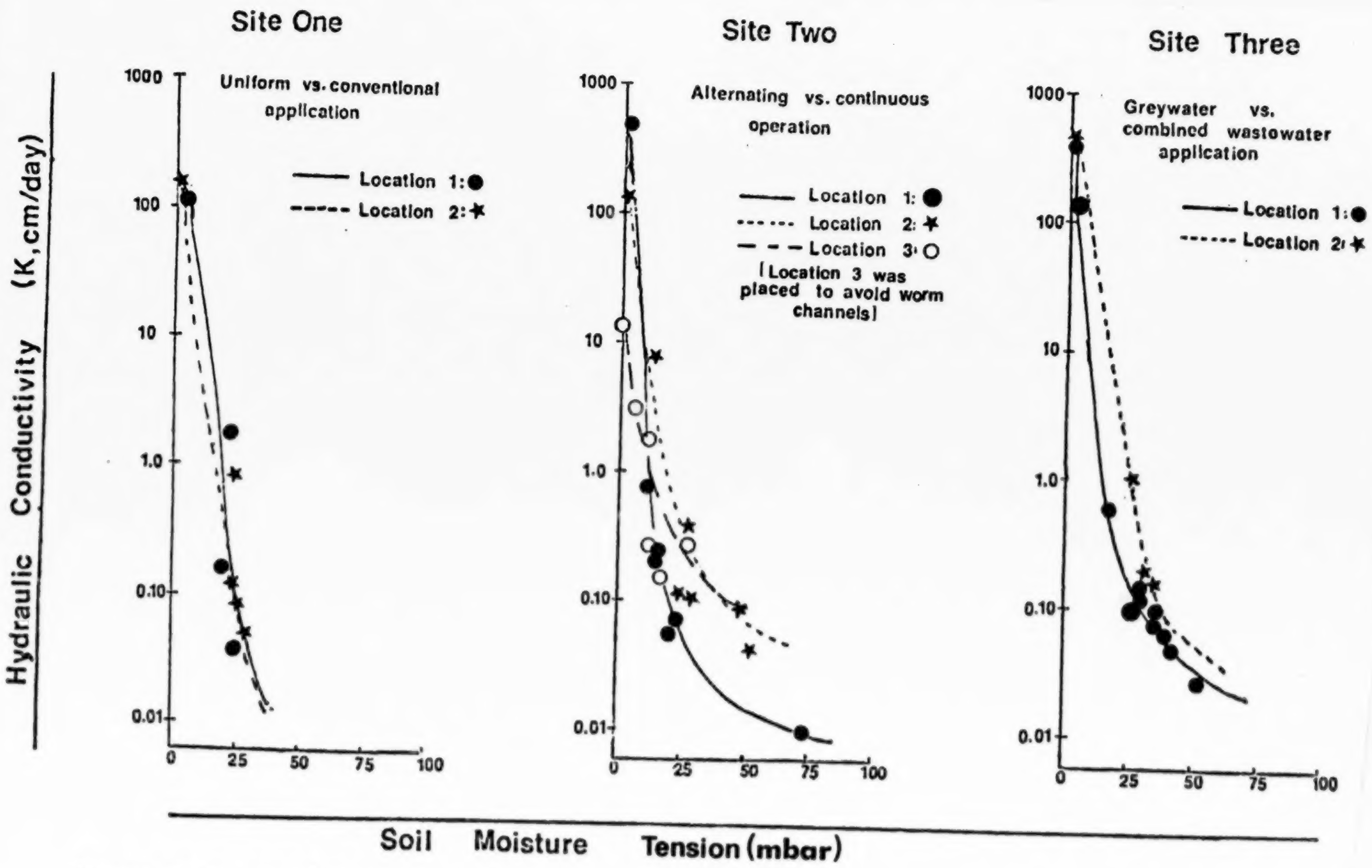


Figure 6-32. Hydraulic conductivity vs. soil moisture tension at each site.

Figure 6-32. Hydraulic conductivity vs. soil moisture tension at each site.

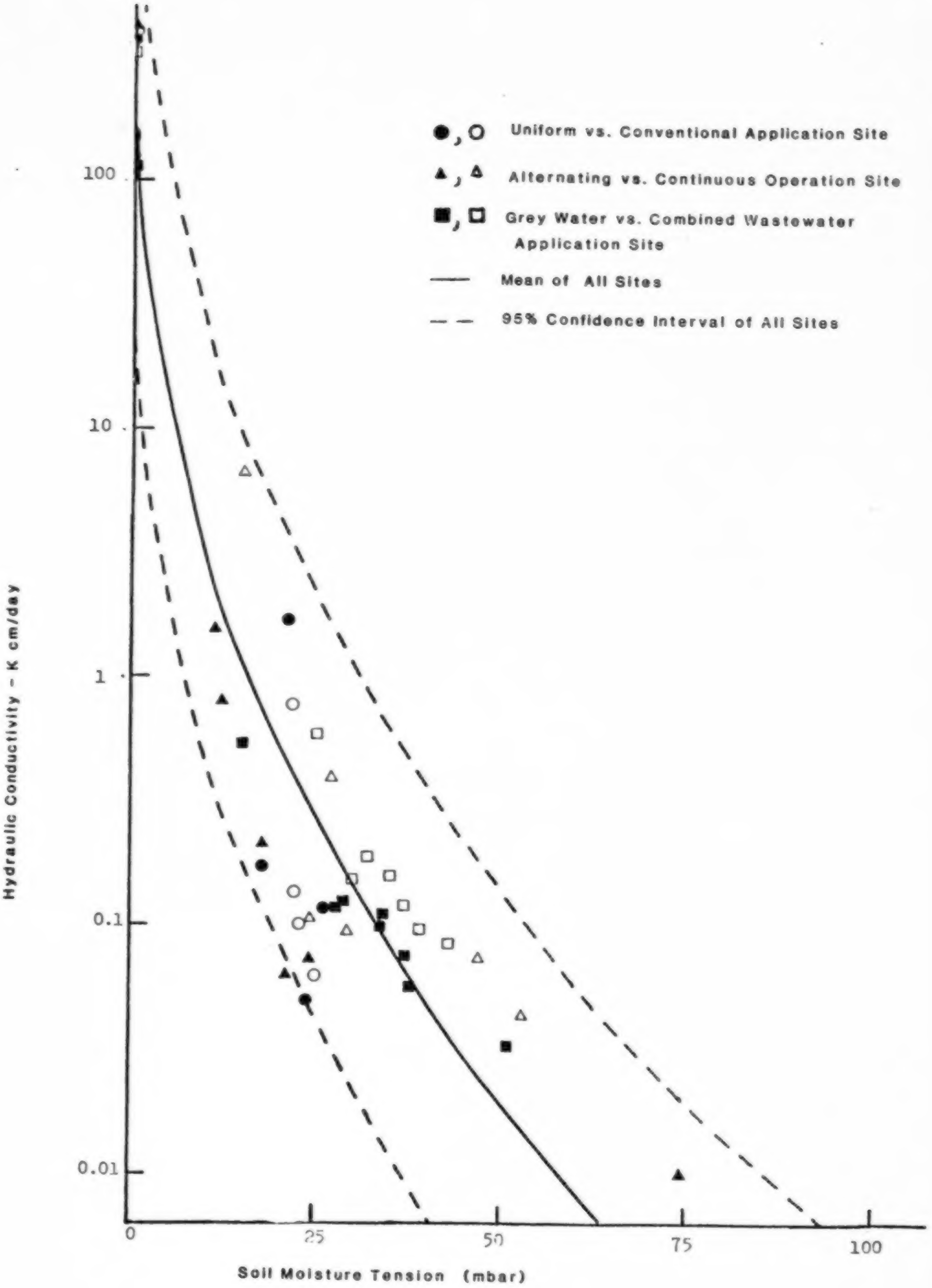


Figure 6-33. Hydraulic conductivity by the crust test method for all sites with plot of 95% confidence interval.

Biopore study--Biopores were counted ocularly from transparent photographic slides and categorized into convenient pore diameter groups. The frequency of occurrence and cumulative area of these biopore size groups was examined for each cell. Table 6-11 summarizes the biopore size distribution and related data. Also, the relative flow for these biopores, proportional to the fourth power of the radius, is reported.

The smallest biopore size group, with mean diameter of about 1.25 mm, is probably caused by the activity of ants such as Formica cinerea (Denning et al., 1973). Larger biopores, ranging from about 1.5 to 8.0 mm in diameter, are probably made by worms of the species Lumbricus terrestris and Aporrectodea tuberculata (Brady, 1974; Helmke et al., 1979) and other similarly sized soil fauna. Figure 6-6 depicts the character and distribution of biopores in an exemplary cell-infiltrative surface.

The biopore size distribution was evaluated to determine the effect of these pores upon other field measurement parameters. Thus far, no relationship has been established between field measurements of infiltration rate, or soil moisture tension, and number, area, or relative flow of any biopore size category. Similarly, no relationship has been found between these field measurements and total combined area or total relative flow of all biopore size groups. However, the initial crust tests conducted at Site 2 showed that at the wettest range of the test, placement of the testing apparatus to avoid worm channels resulted in significantly slower hydraulic conductivity rates (Fig. 6-32). Other workers (Skopp, 1980) have shown that, in laboratory experiments, these macropores have a tremendous positive impact on through-flow rates so that "short-circuiting" of the infiltrating fluid may be highly significant.

The failure to correlate biopore parameters with hydraulic behavior here suggests two problems: (1) the continuity of these biopores is not fully defined, and (2) the effects of these pores upon a field soils' capacity to effectively treat STE is not well understood.

Monitoring--

Climatic conditions--Construction of the experimental soil absorption cell systems was completed in fall 1978 at Site 1. Dosing at this site was begun December 5, 1978. Monitoring of climatic conditions was initiated in fall 1978. A summary of pertinent climatic data for Arlington Experimental Farms for October 1978 to October 1979 is presented in Table 6-12. A cursory examination of these environmental conditions as they might affect the experimental absorption systems yielded no noteworthy results.

Wastewater characterization--

Quantitative characterization--The cumulative volume of wastewater effluent and tapwater added to the soil absorption cells at the three sites is summarized in Table 6-13. Presented in this table is the loading data for the loading rate (mean design daily loading = 2 cm/day), and two and four times this rate. It should be pointed out that these rates (2, 4 and 8 cm/day) were mean design rates based on both soil characteristics and the

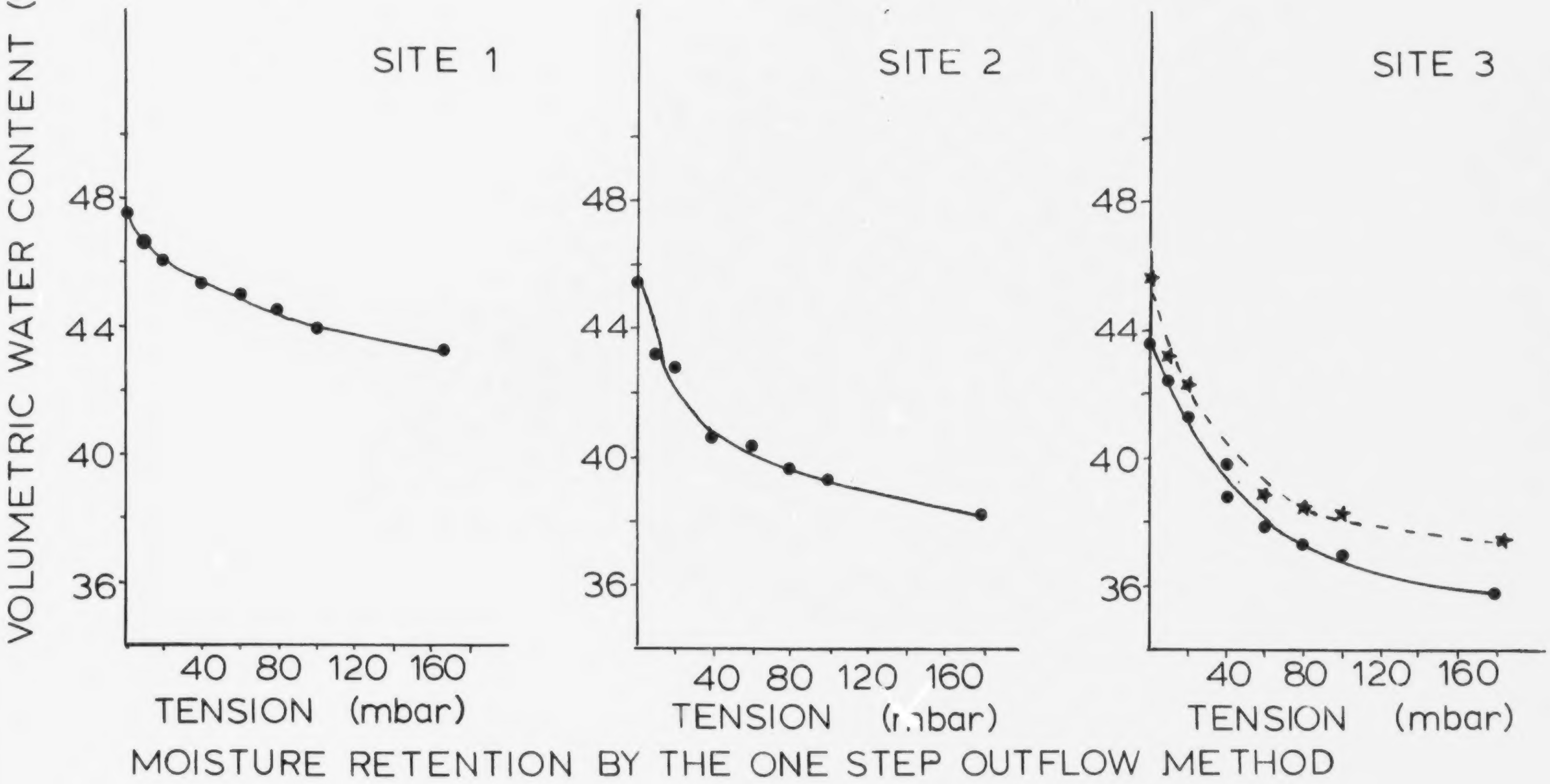
Table 6-11. Size distribution, area, and relative flow characteristics of biopores in soil absorption cell infiltrative surfaces.

Site	Biopore group	Biopore* size(mm)	Number		Area		Relative flow**	
			x	SD		SD	x	SD
1	1	1.53 (1.25)	256.7	84.4	321.0	105.5	783.7	206.1
2	1	1.53 (1.25)	274.2	75.8	342.2	95.7	835.4	185.1
3	1	1.27 (1.00)	222.1	23.0	222.1	23.0	222.1	23.0
1	2	1.53-6.12 (3.85)	119.6	31.2	460.6	120.0	101,196	26,364
2	2	1.53-6.13 (3.85)	67.4	19.4	259.7	74.8	57,057	16,434
3	2	1.27-5.10 (3.19)	71.6	20.0	232.0	64.1	24,024	6,637
1	3	6.12-8.00 (6.50)	4.4	3.2	28.0	20.8	51,588	37,129
2	3	6.13-8.00 (6.50)	1.2	1.3	7.7	8.7	13,656	15,477
3	3	5.10-8.00 (6.00)	6.2	3.8	40.4	21.3	52,358	27,605
1	All	8.00 (2.13)	--	--			153,569	--
2	All	8.00 (1.78)	--	--	612.9	119.0	71,549	--
3	All	8.00 (1.63)	--	--	491.9	122.5	76,605	--

*Biopore size refers to range of diameters in each size group. Mean of each group is in parentheses.

**Relative flow was computed by assigning arbitrarily a value of 1.0 to a pore diameter of 1.0 mm; values for larger diameters were calculated assuming flow proportional to the 4th power of the radius.

Figure 6-34. Hydraulic conductivity vs. soil moisture tension at all sites.



projected wastewater effluent volume available. As shown in Table 6-13, the actual loading rates differ somewhat from the design loading rates, particularly at Site 3 where the actual loading has been substantially lower than the design loading rates. This is because the two wastewater effluents and the tapwater control are applied to the soil cells at the same time to avoid confounding the results of the study with different application dynamics for each set of soil cells. However, it has resulted in a lowered available effluent flow. An example of the reason for this follows. The septic tank effluent sump for the greywater can fill to the high level when the sump for the combined wastewater is below its high level. Since an application cycle to the cells only occurs when both sumps are at the high level, any additional flow to the greywater sump results in an overflow to the overflow basin. Hence, a lower available flow occurs.

To simulate the intermittent trickling of wastewater onto the soil which is typical of a conventional septic tank/soil absorption system, the wastewater effluents and tapwater were applied to the soil cells in many intermittent small doses at a single point above the cell center. This was the loading scheme for all the soil cells at Sites 2 and 3 and half of the cells at Site 1. The other half of the soil cells at Site 1 were loaded an average of once a day, through a mini-distribution system which dispersed the effluent over the soil infiltrative surface. At each site, the pattern of application of wastewater to the soil cells depended entirely upon the particular residential wastewater generation pattern. Figures 6-35 through 6-40 are presented to illustrate the variation in wastewater loading to the soil cells between sites and with time.

Qualitative characterization--The qualitative characteristics of the wastewater effluents applied to the soil absorption cells are presented in Table 6-14. As shown, the combined wastewater effluents at all three sites were similar for most parameters. A notable exception was the mean BOD5 at Site 1 which was approximately 2/3 higher than at Sites 2 and 3. The qualitative properties of the combined wastewater effluent examined here are well within the range of values reported in previous investigations.

Comparison of the two wastewater effluents and the tapwater control at Site 3 indicated their qualitative differences. The combined wastewater and grey.water were found to be similar in quality with respect to most parameters, with the exception of the nitrogen levels,which were considerably higher in the combined wastewater. Surprisingly, the BOD5 and COD in the greywater were somewhat higher than in the combined wastewater. Further, the levels of bacteria detected, including such indicator organisms as total and fecal coliforms, were essentially the same as the levels in the combined wastewater. The tapwater control was of a much higher quality than either wastewater effluents, exhibiting no BOD_5 or COD. The low levels of nitrogen and bacteria measured in this tapwater were most likely due to minor amounts of soil material or other extraneous matter that inadvertently entered the tapwater sump basin occasionally.

Table 6-12. Climatic conditions at Arlington Experimental Farms, October 1978 - October 1979.

Table Temperature and precipitation at Arlington Experimental Farms
October, 1978 - September, 1979

YEAR	1978				1979									
MONTH	OCT	NOV	DEC	YEAR TOTAL	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT
MEAN TEMPERATURE °C (°F)	8.9 (48.1)	1.8 (35.4)	-6.8 (19.6)	6.6 (44.0)	-14.5 (5.8)	-11.8 (10.7)	-1.2 (29.7)	5.6 (42.1)	13.3 (56.0)	19.0 (66.2)	21.0 (69.9)	19.7 (67.5)	16.8 (62.4)	9.0 (48.3)
TEMPERATURE - DEPARTURE FROM NORMAL	-18.7 (-1.8)	-17.3 (0.7)	-18.9 (-2.1)	-18.3 (-1.0)	-23.8 (-11.0)	-23.1 (-9.6)	-17.5 (-0.5)	-19.5 (-3.2)	17.7 (0.0)	18.5 (1.4)	-17.8 (-0.2)	-18.4 (-1.2)	-16.2 (2.7)	-18.6 (-1.6)
MAXIMUM TEMPERATURE	23.8 (75.0)	22.2 (72.0)	5.0 (41.0)		-2.7 (27.0)	2.7 (37.0)	13.3 (56.0)	22.7 (73.0)	28.8 (84.0)	30.0 (86.0)	30.0 (86.0)	29.4 (85.0)	28.8 (84.0)	25.0 (77.0)
AVERAGE MAXIMUM TEMPERATURE	14.2 (57.7)	6.9 (44.5)	-2.2 (28.0)		-9.8 (14.3)	-6.3 (20.6)	3.2 (37.9)	11.3 (52.5)	20.3 (68.7)	25.6 (78.1)	27.3 (81.3)	24.8 (76.8)	24.3 (75.8)	14.5 (58.2)
MINIMUM TEMPERATURE	-1.6 (29.0)	-17.2 (1.0)	-25.5 (-14.0)		-31.6 (-25.0)	-30.0 (-22.0)	-19.4 (-3.0)	-11.6 (11.0)	-0.5 (31.0)	5.5 (42.0)	7.2 (45.0)	5.0 (41.0)	2.7 (37.0)	-6.6 (20.0)
AVERAGE MINIMUM TEMPERATURE	3.5 (38.4)	-3.2 (26.2)	-11.6 (11.1)		16.2 (-2.8)	-17.3 (0.8)	-5.8 (21.5)	-0.1 (31.7)	6.2 (43.2)	12.3 (54.2)	14.7 (58.5)	14.5 (58.1)	9.4 (49.0)	3.5 (38.4)
TOTAL PRECIPITATION (WATER EQUIVALENT) mm (in.)	42.1 (1.66)	80.7 (3.18)	24.3 (.96)	892.3 (35.13)	29.4 (1.16)	17.5 (.69)	77.7 (3.06)	42.4 (1.67)	69.3 (2.73)	96.0 (3.78)	68.3 (2.69)	194.8 (7.67)	3.8 (.15)	74.6 (2.94)
PRECIPITATION - DEPARTURE FROM NORMAL	-12.7 (-.50)	33.2 (1.31)	-12.9 (-.51)	123.9 (4.88)	-2.2 (-.09)	-6.6 (-.26)	28.7 (1.13)	25.1 (0.99)	44.4 (1.75)	-13.9 (-.55)	-28.4 (-1.12)	117.3 (4.62)	-81.5 (-3.21)	19.8 (0.78)
PRECIPITATION - GREATEST SINGLE DAY	16.2 (.64)	41.6 (1.64)	10.6 (.42)		9.6 (.38)	7.1 (.28)	21.8 (.86)	10.6 (.42)	27.1 (1.07)	36.0 (1.42)	23.6 (.93)	97.7 (3.85)	3.5 (.14)	17.7 (.70)

Table 6-13. Summary of wastewater loadings to the soil absorption cells.

	Site			Site			Site		
Parameter	1	1	1	2	2	2	3	3	3
Design daily loading (cm/day)	2	4	8	2	4	8	2	4	8
Actual daily loading									
(cm/day)†	2.2	4.2	8.2	2.1	4.1	8.2	1.2	2.3	4.5
(gal/d/ft^2)†	0.51	0.97	1.89	0.47	0.95	1.83	0.27	0.54	1.05
Cumulative loading									
(m)	7.47	14.33	28.35	2.89	5.77	11.26	1.01	2.02	3.94
(gal)	1214	2331	4610	469	939	1830	165	329	644
Applications‡									
(no./d)†	8.18 (1.02)	8.18 (1.02)	8.18 (1.02)	8.25	8.25	8.25	4.64	4.64	4.64
(no.)	2998 (375)	2998 (375)	2998 (375)	1155	1155	1155	405	405	405
Data period	12/5/78 to 1/7/80			8/1/79 to 1/7/80			9/25/79 to 1/7/80		
Total days¶	398.2			159.2			104.2		
Full operation days	364.0			133.3			81.1		

†All daily values based upon days of full system operation only.

‡For conventional application cells, each application represents 12.5% of the design daily loading, for once-daily-uniform application cells, each application represents 100% of the design daily loading.

§Number in parentheses is for once-daily-uniform application cells.

¶Includes minimal periods when system was inoperative due to equipment malfunction, maintenance, etc.

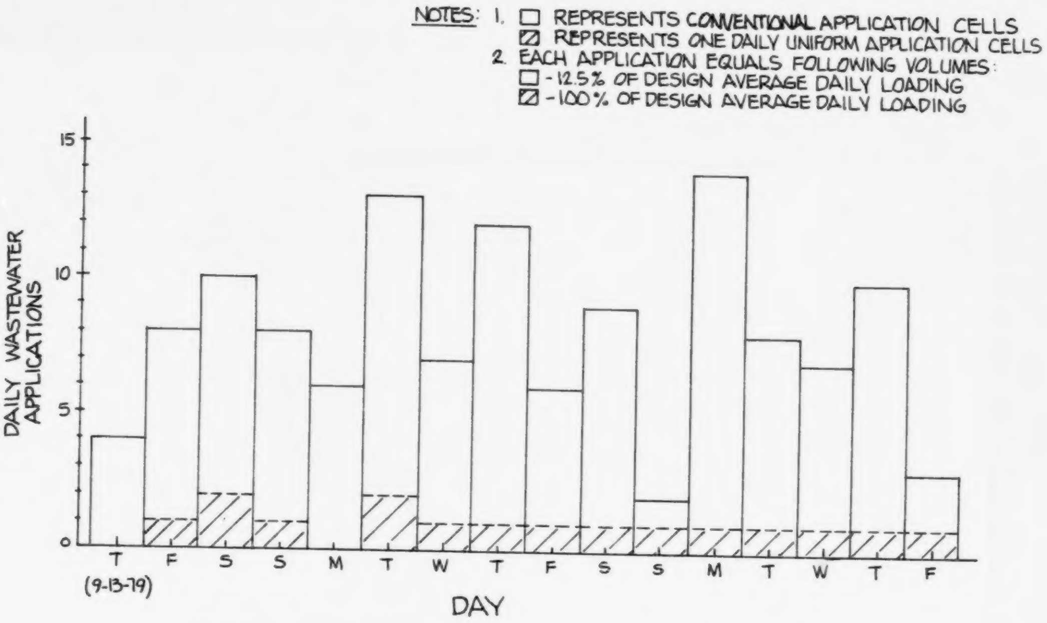

NOTES: 1. ☐ REPRESENTS CONVENTIONAL APPLICATION CELLS
▨ REPRESENTS ONE DAILY UNIFORM APPLICATION CELLS
2. EACH APPLICATION EQUALS FOLLOWING VOLUMES:
☐ - 12.5% OF DESIGN AVERAGE DAILY LOADING
▨ - 100% OF DESIGN AVERAGE DAILY LOADING

Figure 6-35. Example of daily fluctuations in wastewater application to soil cells at Site 1.

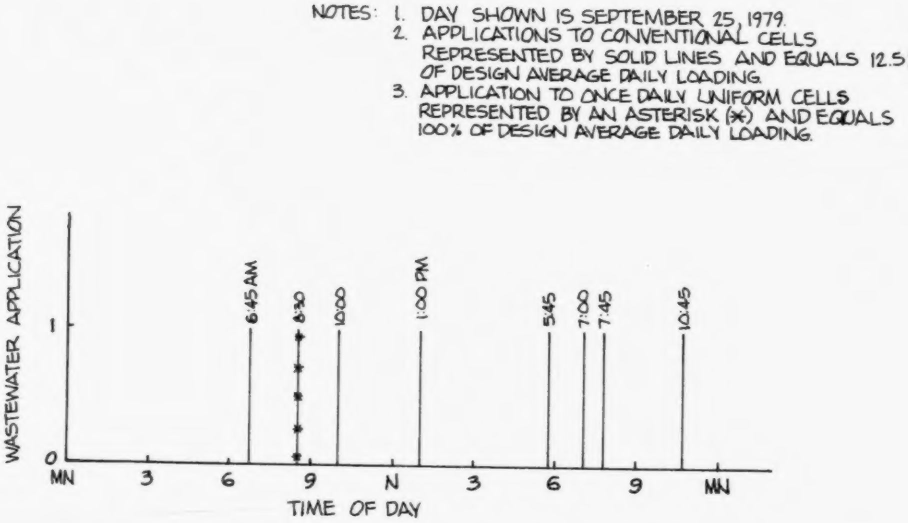
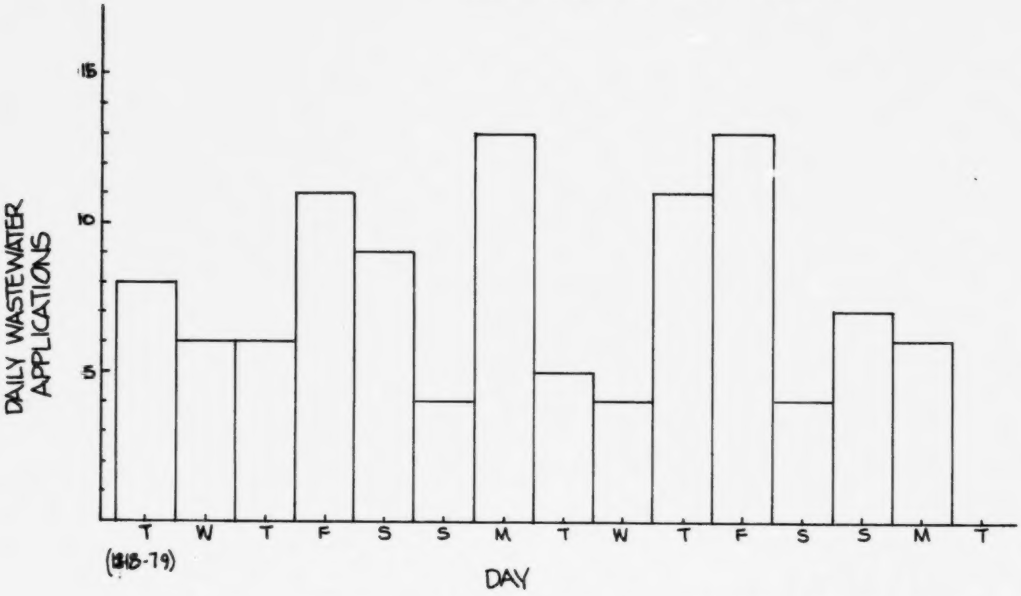

NOTES: 1. DAY SHOWN IS SEPTEMBER 25, 1979.
2. APPLICATIONS TO CONVENTIONAL CELLS REPRESENTED BY SOLID LINES AND EQUALS 12.5% OF DESIGN AVERAGE DAILY LOADING.
3. APPLICATION TO ONCE DAILY UNIFORM CELLS REPRESENTED BY AN ASTERISK (*) AND EQUALS 100% OF DESIGN AVERAGE DAILY LOADING.

Figure 6-36. Example of hourly fluctuations in wastewater application to soil cells at Site 1.



NOTE: EACH APPLICATION EQUALS 12.5% OF DESIGN AVERAGE DAILY LOADING

Figure 6-37. Example of daily fluctuations in wastewater application at Site 2.

NOTES: 1. EACH APPLICATION EQUALS 12.5% OF DESIGN AVERAGE DAILY LOADING.
2. DAY SHOWN IS DECEMBER 22, 1979.

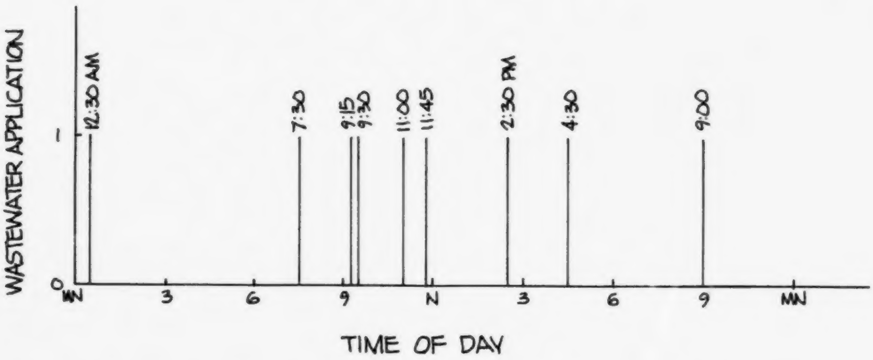


Figure 6-38. Example of hourly fluctuations in wastewater application at Site 2.

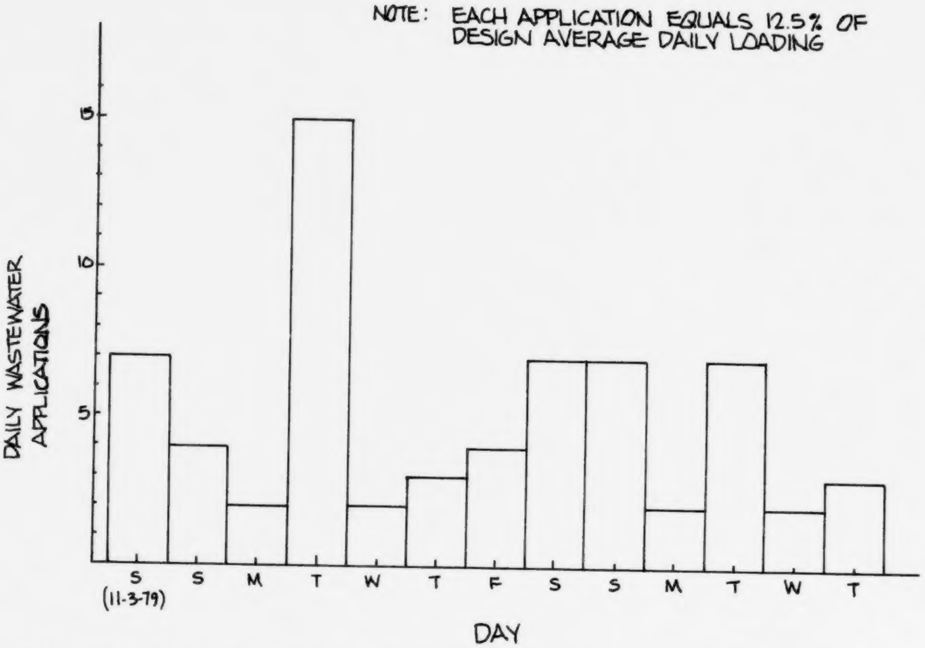


Figure 6-39. Example of daily fluctuations in wastewater application to soil cells at Site 3.

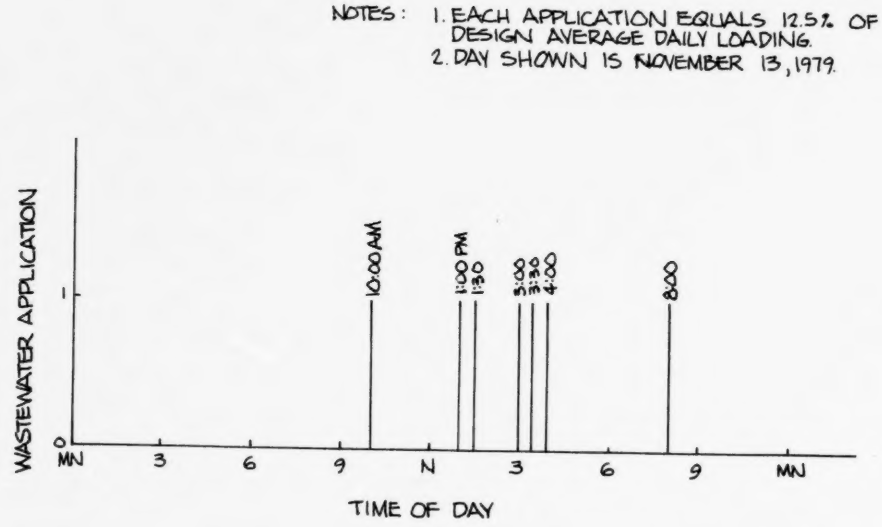


Figure 6-40. Example of hourly fluctuations in wastewater application to soil cells at Site 3.

Table 6-14. Mean septic tank effluent quality with ranges.

	Site 1	Site 2	Site 3		
Parameter	Combined wastewater	Combined wastewater	Combined wastewater	Greywater*	Tapwater control**
BOD$_5$ (mg/L)	153(10)+	92(7)	90(5)	104(5)	0(4)
	92-225	45-111	58-120	74-156	--
COD (mg/L)	265(9)	223(6)	254(5)	339(5)	0(2)
	157-388	111-291	80-440	182-474	--
Suspended solids	44(10)	44(6)	--	--	--
(mg/L)	22-75	26-104	--	--	--
Volatile suspended	37(10)	33(2)	--	--	--
solids (mg/L)	12-67	30-36	--	--	--
Total nitrogen	--	37(5)	46(4)	13.4(4)	1.6(2)
(mg N/L)	--	31-47	17-57	12-16	0.8-2.4
Ammonia nitrogen	41(9)	32.6(6)	32.4(3)	5.1(3)	0.4(2)
(mg N/L)	32.8-64.8	25.6-39.3	1.4-5.1	4.1-6.6	0.2-0.6
Total phosphorus	18.4(11)	11.1(1)	--	--	--
(mg P/L)	8.5-27	--	--	--	--
	-(9)	--	--(2)	--(2)	--(2)
pH	7.5-8.0	--	6.3-7.3	6.4-7.5	7.0-8.5
Alkalinity	--	456(5)	505(5)	403(5)	270(5)
(mg $CaCO_3$/L)	--	400-480	432-548	384-428	263-280
Hardness	--	309(7)	306(5)	317(5)	290(5)
(mg $CaCO_3$/L)	--	276-324	280-352	276-364	284-308
Turbidity (NTU)	--	42(4)	40(4)	54(4)	1(4)
-	--	13-92	24-54	30-68	--
Temperature (^{0}C)	--	--	--(4)	--(4)	--(4)
	--	--	3-11	4-8	3-9.5
Total bacteria	--(9)	--(6)	--(5)	--(5)	--(4)
(Log$_{10}$#/L)	8.08-9.76	8.88-9.54	7.58- 9.48	8.48- 9.47	4.53- 7.48
Total coliforms	--(9)	--(5)	--(5)	--(5)	--(5)
(LOg$_{10}$#/L)	7.65-8.52	6.90-8.90	7.38- 8.90	5.90-8.90	1-4.3
Fecal coliforms	--(9)	--(6)	--(5)	--(5)	--(4)
(Log$_{10}$#/L)	7.60-7.66	6.04-8.43	6.78- 7.58	5.77-7.64	1-2.2

*Consists of typical household fixture waste flows excluding garbage disposal wastes and toilet wastes.

**Consists of fresh tapwater periodically added to a sump basin and held for a variable period of time prior to application the the soil cells.

+Number of analyses.

Monitoring of soil absorption cells--

Infiltration rates--Bottom area infiltration rates are reported for each site in Table 6-15. These measurements accurately reflect changes in soil hydraulic properties as influenced by rates, types, and methods of effluent application, over an extended time period.

Infiltration rates have been most informative at Site 1 where more than one year of data has been collected. These data are presented graphically in Figure 6-41. Each point plotted represents the treatment mean of multiple measurements for each cell -- three replicate cells per treatment -- for each date reported. Figure 6-41, Site 1, depicts several noteworthy features. The trend of abrupt decline in infiltration rate from the initial measurements until March 1979 documents the impact of beginning application of effluent on all treatments. Measurements made during the period from March 1979 to May 1979 indicate fluctuation in hydraulic behavior that might be associated with spring-time climatic influences. Partially-frozen soil conditions, high or perched groundwater conditions due to snowmelt, added to heavy rains may influence readings taken during these periods. The long-term trend from November 1978 to October 1979 shows the general decline in infiltration rate. This rate has changed most dramatically for the 8 cm/day trickle (4C) treatment, from nearly 250 cm/day in November 1978 to less than 50 cm/day in October 1979. Because the initial and final measurements were taken under similar climatic and seasonal conditions, they should be considered highly comparable.

The final ranking of Site 1 infiltration rates for the respective treatments in October 1979, in Figure 6-41 and Table 6-15, is of particular interest. Infiltration rates of the once-daily-uniform treatments (1D, 2D, and 4D) at all application rates were higher than those of the eight-times-daily conventional treatments (1C, 2C, and 4C). Moreover, infiltration rates also ranked precisely according to both rate of application as well as method of application: > treatment 1D > treatment 2D > treatment 4D >treatment 1C > treatment 2C > treatment 4C.

These results, and the relative values of each mean presented, suggest that for the soil conditions examined in this study, once-daily-uniform applications of STE maintain distinctively higher infiltration rates after one year of effluent dosing than conventional applications. These rates may be partially explained by the theory that effluent applied conventionally -- at any rate--keeps the soil medium wetter for a longer period. Thus, this method of application produces conditions in which soil crusting may more likely occur, and hence, infiltration rates decline more rapidly. It should be stressed that these results are preliminary and have not been subjected to rigorous statistical analysis. However, continued intensive monitoring of this parameter, accompanied by analysis of variance of existing and new data, is planned.

Table 6-15. Soil absorption cell infiltration rates (cm/day).

Treatment code[†]	Cell no.	Nov. 1979	$\bar{x}$	SD	Mar. 1979	$\bar{x}$	SD	Apr. 1979	$\bar{x}$	SD	June 1979	$\bar{x}$	SD	Oct. 1979	$\bar{x}$	SD
								Site #1, Turkey Farm								
1C	1	129	161.1	24.4	--	--	--	29	56.6	33.3	42	61.6	18.9	59	74.3	26.1
	2	136						47			63			59		
	3	210						94			80			104		
1D	4	188	187.0	0.6	--	--	--	69	89.3	21.0	83	109.6	49.4	113	103.4	16.7
	5	187						88			79			73		
	6	187						111			167			124		
2C	7	184	202.2	28.0	73	40.8	30.8	139	105.2	31.8	86	71.4	15.1	34	55.5	19.2
	8	188			11			76			56			71		
	9	234			39			100			73			62		
2D	10	239	208.5	34.7	131	61.2	60.9	129	97.9	29.4	122	108.7	22.5	158	106.2	45.4
	11	216			32			71			121			73		
	12	171			20			94			83			87		
4C	13	234	218.5	30.5	42	65.4	39.9	83	80.2	16.7	53	95.9	36.9	42	14.1	--
	14	183			112			96			119			0[‡]		
	15	238			43			62			116			0[‡]		
4D	16	213	234.4	69.7	188	143.8	43.9	144	126.6	27.3	180	142.6	34.1	82	85.5	4.4
	17	312			100			95			134			85		
	18	178			143			141			113			90		
All cells			201.4	41.2		77.8	56.3		92.6	31.9		98.3	38.3		78.7	37.0

[†] 1C is 1 x the basic design loading rate (2 cm/day), conventionally applied. 1D is 1 x the basic design loading rate (2 cm/day), dosed once daily. 2C is 2 x the basic design loading rate (2 cm/day), conventionally applied. 2D is 2 x the basic design loading rate (2 cm/day), dosed once daily. 4C is 4 x the basic design loading rate (2 cm/day), conventionally applied. 4D is 4 x the basic design loading rate (2 cm/day), dosed once daily.

[‡] Ponding precluded infiltration tests.

-continued-

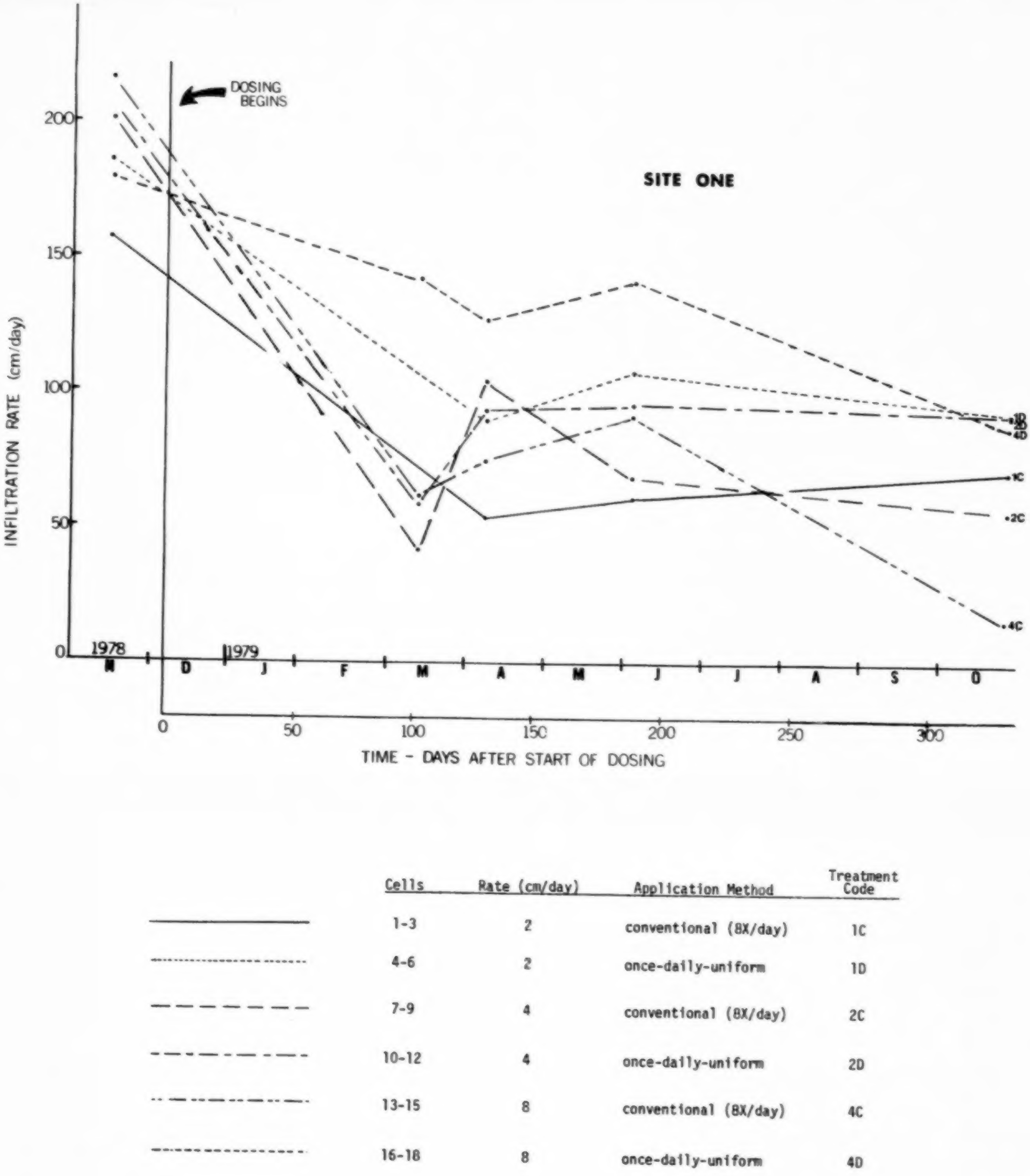
Table 6-15. (continued).

Treatment code†	Cell no.	June 1979	$\overline{x}$	SD	Nov. 1979	$\overline{x}$	SD
		Site #2, Sheep Farm					
4C	1	129	129.4	3.7	161	152.4	25.0
	2	126			124		
	3	133			172		
4A	4	162	136.3	37.5	220	155.1	73.0
	5	153			169		
	6	93			76		
2C	7	163	135.9	35.7	251	176.8	100.8
	8	149			217		
	9	96			62		
2A	10	168	126.8	36.9	256	162.2	81.0
	11	117			118		
	12	96			113		
1C	13	246	161.8	82.2	233	189.3	68.8
	14	159			225		
	15	81			110		
1A	16	277	181.9	82.9	382	247.9	124.5
	17	145			226		
	18	124			136		
2CO	19	176	146.0	25.6	254	181.5	67.2
	20	129			169		
	21	134			121		
4NS	22	144	135.5	17.4	183	124.1	52.3
	23	116			85		
	24	147			104		
All cells			144.2	44.1		173.7	74.6

† 4C is 4 x (2 cm/day), applied continuously. 4A is 4 x (2 cm/day), with alternating rest periods. 2C is 2 x (2 cm/day), applied continuously. 2A is 2 x (2 cm/day), with alternating rest periods. 1C is 1 x (2 cm/day), applied continuously. 1A is 1 x (2 cm/day), with alternating rest periods. 2CO is 2 x (2 cm/day), to be rejuvenated with hydrogen peroxide. 2NS is 2 x (2 cm/day), with no restricting sidewalls.

Treatment code†	Cell no.	Aug. 1979	$\overline{x}$	SD	Nov. 1979	$\overline{x}$	SD
		Site #3, Solar Home					
2T	3	222	248.9	37.7	140	175.6	50.3
	6	276			211		
4T	2	278	341.1	89.6	259	256.1	3.9
	5	404			253		
8T	1	198	238.9	58.2	309	295.0	19.6
	4	280			281		
2G	7	331	252.9	76.2	309	280.9	74.8
	8	181			196		
	9	247			338		
4G	10	177	211.8	87.2	253	230.7	44.0
	11	148			180		
	12	311			259		
8G	13	281	235.2	82.4	281	213.6	58.5
	14	140			183		
	15	284			177		
2C	22	230	229.6	16.1	206	184.8	21.1
	23	146			163		
	24	213			186		
4C	19	244	232.2	32.3	244	204.1	35.0
	20	257			188		
	21	196			180		
8C	16	169	211.0	37.0	186	185.0	6.3
	17	238			179		
	18	227			191		
All cells			240.7	60.7		222.9	53.4

† 1T is 1 x (2 cm/day), tapwater. 2T is 2 x (2 cm/day), tapwater. 4T is 4 x (2 cm/day), tapwater. 1G is 1 x (2 cm/day), greywater. 2G is 2 x (2 cm/day), greywater. 4G is 4 x (2 cm/day), greywater. 1C is 1 x (2 cm/day), combined wastewater. 2C is 2 x (2 cm/day), combined wastewater. 4C is 4 x (2 cm/day), combined wastewater.



	Cells	Rate (cm/day)	Application Method	Treatment Code
————————	1-3	2	conventional (8X/day)	1C
··················	4-6	2	once-daily-uniform	1D
— — — — — —	7-9	4	conventional (8X/day)	2C
— - — - — - —	10-12	4	once-daily-uniform	2D
·· — - — - — · —	13-15	8	conventional (8X/day)	4C
-·-·-·-·-·-·-·-	16-18	8	once-daily-uniform	4D

Figure 6-41. Infiltration rate vs. time, by treatment - Site 1.

Table 6-15 also presents the infiltration rate measurements at Sites 2 and 3. Only two data sets are available at this writing for each treatment at each of these sites, and these data are from a rather short period beginning at dosing of effluent. The variability of the data collected for these sites thus far makes it difficult to determine whether the trends are genuinely treatment-associated or if the trends are general over all treatments.

Soil moisture tension--Soil moisture tension (SMT) was monitored with tensiometers at four locations under each soil absorption cell at each site. The volume of data provided by these instruments is quite large, roughly one measurement per tensiometer per week, and all of the data collected have not yet been carefully examined. Data for selected weeks for each site were analyzed using the Statistical Analysis System (Barr et al., 1976). This analysis served several purposes: (1) reorganization of a large volume of data; (2) correction for calibration values attributed to individual instrument depth relative to manometer placement; (3) algorithmic discarding of extraneous instrument values; (4) preliminary statistical analysis of the data by numerous categories; and (5) determination of SMT trends over varying time intervals for both trouble-shooting and interpretive purposes. In the following interpretation of data, it is important to remember that these data represent only 10 to 20% of the dates on which data were collected, and that the analyses conducted thus far are preliminary. Future analyses will be attempted, including analysis of variance, to detect statistically significant differences at particular categorical levels, such as treatment, rate, method and date.

Figures 6-42 and 6-43 present SMT as a quarterly mean for the two tensiometer depths below the cell infiltrative surface at Site 1. Soil moisture tension values at the 5 cm depth indicate a general decline over the first three quarters of operation followed by increasing SMT for some treatments. This wetting-up and drying-out of some treatments may be partially explained by the development of organic crusts at the infiltrative surface, which exert subcrust tensions as the crust impedes downward water movement.

Preliminary analyses of SMT provide some insight into changes in water regime under the soil absorption cells. The SMT of treatment 4C at 5 cm seems to indicate the progressive development of a biological clogging layer during the monitoring period. This is evidenced by a wetting trend during the first six months, followed by a distinctive drying out (increased SMT). The behavior of this treatment at the 50 cm depth may indicate the same trends in a more dramatic -- if variable -- fashion. If crusting is used to explain which treatments are developing subcrust tensions at Site 1, then the SMT data appear to corroborate the infiltration data already discussed. Where they occur, crusting and large biopores may interact to exert great influence on the soil water regime beneath the soil absorption cell systems. These data reflect the complexity of the systems being studied; hence, further study will be required to fully explore and explain the mechanisms involved.

Site One

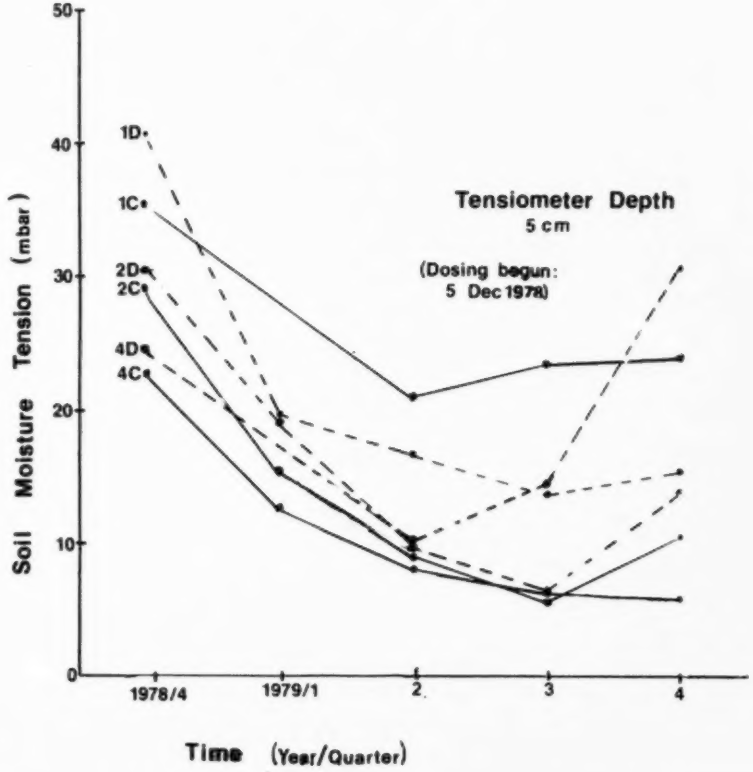


Figure 6-42. Soil moisture tension at 5 cm depth - Site 1.

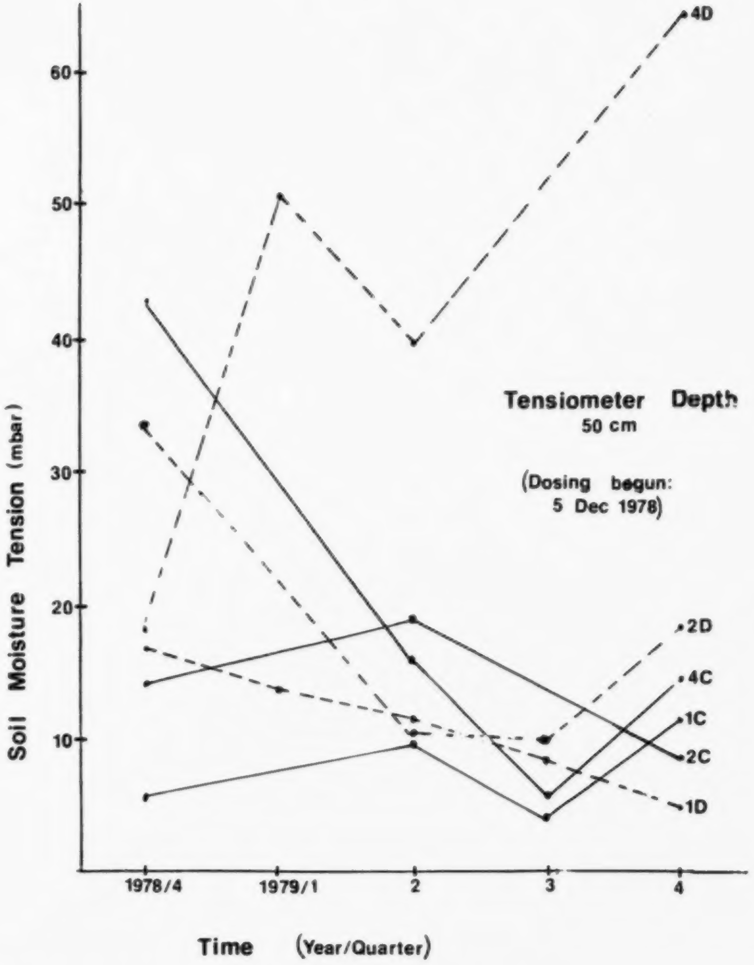


Figure 6-43. Soil moisture tension at 50 cm depth - Site.

Figure 6-44, Site 2, shows SMT trends by application rate over the period July to December 1979. Here, a distinct SMT decline occurs abruptly after dosing is begun, followed by a leveling-off for all rates and depths. The final ranking of SMT for the respective application rates is 4 cm/day > 8 cm/day > 2 cm/day for both depths. (Because the process of alternation of effluent application has not yet begun at this site, the continuous and alternating treatments at the various rates were united into a single rate treatment, as shown in Figure 6-44.). The substantially wetter conditions at the lowest application rate, reflected in the higher subcrust tensions at 4 and 8 cm/day, may possibly indicate that early crusting is occurring. The fact that the 4 cm/day treatments are drier than the 8 cm/day treatments at both depths may be at least partially explained by some flushing out of the biological crust at the higher rate. Apparently, when twice as great a hydraulic load is applied, some of that load penetrates through the crust to the tensiometers, resulting in lower SMT response (wetter conditions). These differences have not been subjected to intensive statistical analysis, however, and could be only incidental to the equilibrium period or time of year.

Because of the brief period since dosing was begun at Site 3, SMT trends are not presented or discussed here.

Ponding observation--Regular inspection of the observation wells in each soil absorption cell has been carried out at each site since dosing was initiated. Persistent ponding above the infiltrative surface, as observed through these wells, is interpreted as an indicator of crust development. These observations may accurately indicate progressive system failure. In any case, such observations reflect the current moisture regime at the infiltrative surface, including the nature of current hydraulic conductivity and water table conditions. Observations of persistent ponding and depths of effluent have been recorded; these data are presented in Table 6-16 for Site 1.

Ponding was first noted at Site 1 in several cells in April and May 1979; this ponding disappeared in all cells after two to three months. These observations were probably associated with the spring thaw of a very heavy snowfall year, which also probably influenced other soil moisture and hydraulic property measurements. Persistent ponding began recurring again at Site 1 in September 1979. Of particular interest is the pattern with which this ponding began. As shown in Table 6-16, the conventional 8 cm/day application cells showed persistent ponding first, followed a few weeks later by the conventional 4 cm/day cells. At this writing, some of the conventional 2 cm/day cells and some of the 8 cm/day and 4 cm/day once-daily-uniform application cells show occasional ponding. The depth and persistence of the ponding has varied, but the frequency has increased in these cells proportional to the time elapsed since initial persistent ponding was observed. Ponding might be expected to fluctuate about some equilibrium level after a certain point. This is because increasing hydraulic head may provide additional force to drive effluent through the crust layer at a rate roughly equivalent to the design loading rate. Eventually, however, total hydraulic failure of the system may occur.

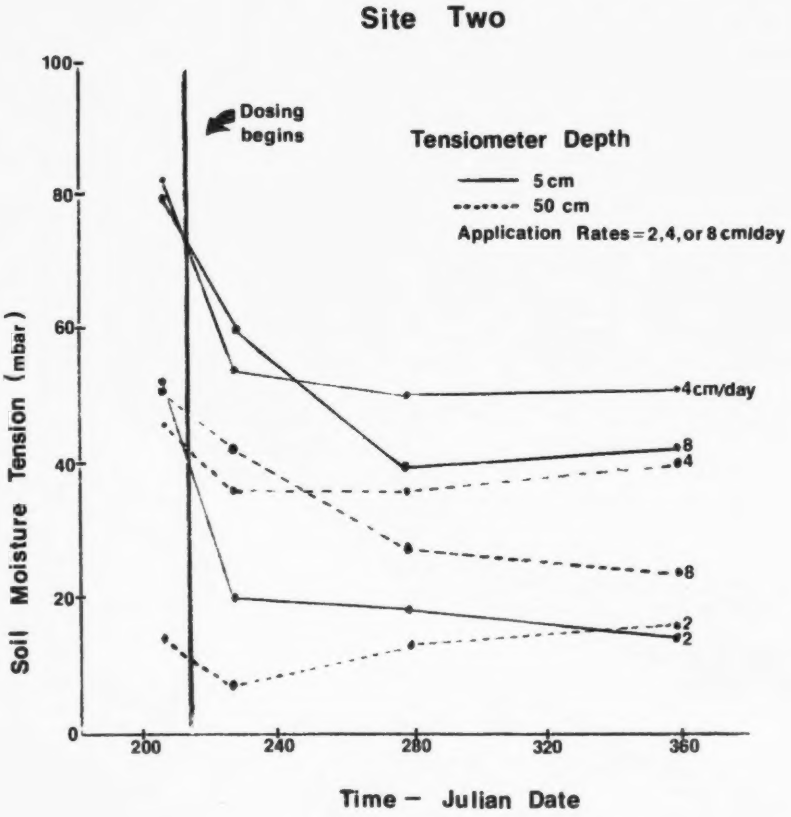


Figure 6-44. Soil moisture tensions at 5 and 50 cm depths - Site 2.

These observations and measurements appear to have considerable potential to provide very valuable information. Continued intensive monitoring of these wells is planned. Also, a network of background wells is being planned to study possible mounding of the residual groundwater table and/or perched water/effluent table as influenced by treatments and rates.

No persistent ponding has been observed at Sites 2 and 3 to date, probably because of the brevity of the monitoring period since dosing was begun. Continued well-monitoring and background studies on these sites are planned.

Thermometric conditions--Soil temperature data have been collected at regular intervals at each site since before dosing was initiated. These data are presented graphically in Figure 6-45 for Site 1.

Data from only three cells instrumented with thermocouples are presented in Figure 6-45. Although not yet subjected to rigorous analysis, some trends are evident. Seasonal climatic trends are easily recognized. Comparing the 2D (dosed 4 cm/day) and 4D (dosed 8 cm/day) treatments, the higher rate seems to cause the soil to be somewhat warmer most of the time. This is expected, especially during cooler weather, since more heat input in the form of effluent should linger in a higher temperature. A comparison of the 4C (conventional 8 cm/day) treatment to the 4D treatment seems to indicate slightly higher temperatures in the more frequently dosed treatment (4C), as expected.

The significance of these slight temperature differences may lie in their impact upon microbial activity. That is, even a slight increase in temperature in one treatment over another may provide the warmer cell with a longer, more effective STE treatment period by giving organisms a longer season and a larger nutrient source.

Table 6-16. Observations of ponding conditions - soil absorption cells, Site 1.†

Treatment code	Cell	12/26/78 thru 6/26/79	7/16	9/11	10/5	11/2	11/26	12/5	12/20	12/28	1/10/80	2/1
IC	1	–	–	–	–	–	–	+	–	–	–	–
	2	–	–	–	–	–	–	–	–	–	–	–
	3	–	+	–	–	–	–	–	–	–	–	–
ID	4	–	–	–	–	–	–	–	–	–	–	–
	5	–	–	–	–	–	–	–	–	–	–	–
	6	–	+	–	–	–	–	–	–	–	–	–
2C	7	–	+	–	–	–	–	+	–	–	–	–
	8	–	–	–	–	–	–	+	1	4	1	4
	9	–	–	–	–	–	–	–	–	–	–	–
2D	10	–	+	–	–	–	–	+	–	–	–	–
	11	–	+	–	–	–	–	–	–	4	–	4
	12	–	+	–	–	–	–	–	–	–	–	–
4C	13	–	+	–	–	+	+	+	6	10	7	7
	14	–	+	–	–	+	+	+	14	17	10	17
	15	–	–	–	–	+	+	+	4	9	7	9
4D	16	–	+	–	–	–	+	+	3	6	4	5
	17	–	+	–	–	–	+	+	–	6	–	2
	18	–	+	–	–	–	+	+	–	8	–	–

† – denotes dry conditions; + denotes ponding, not measured; numerals indicate depth of ponding in cm (this measurement initiated as of 12/20/79).

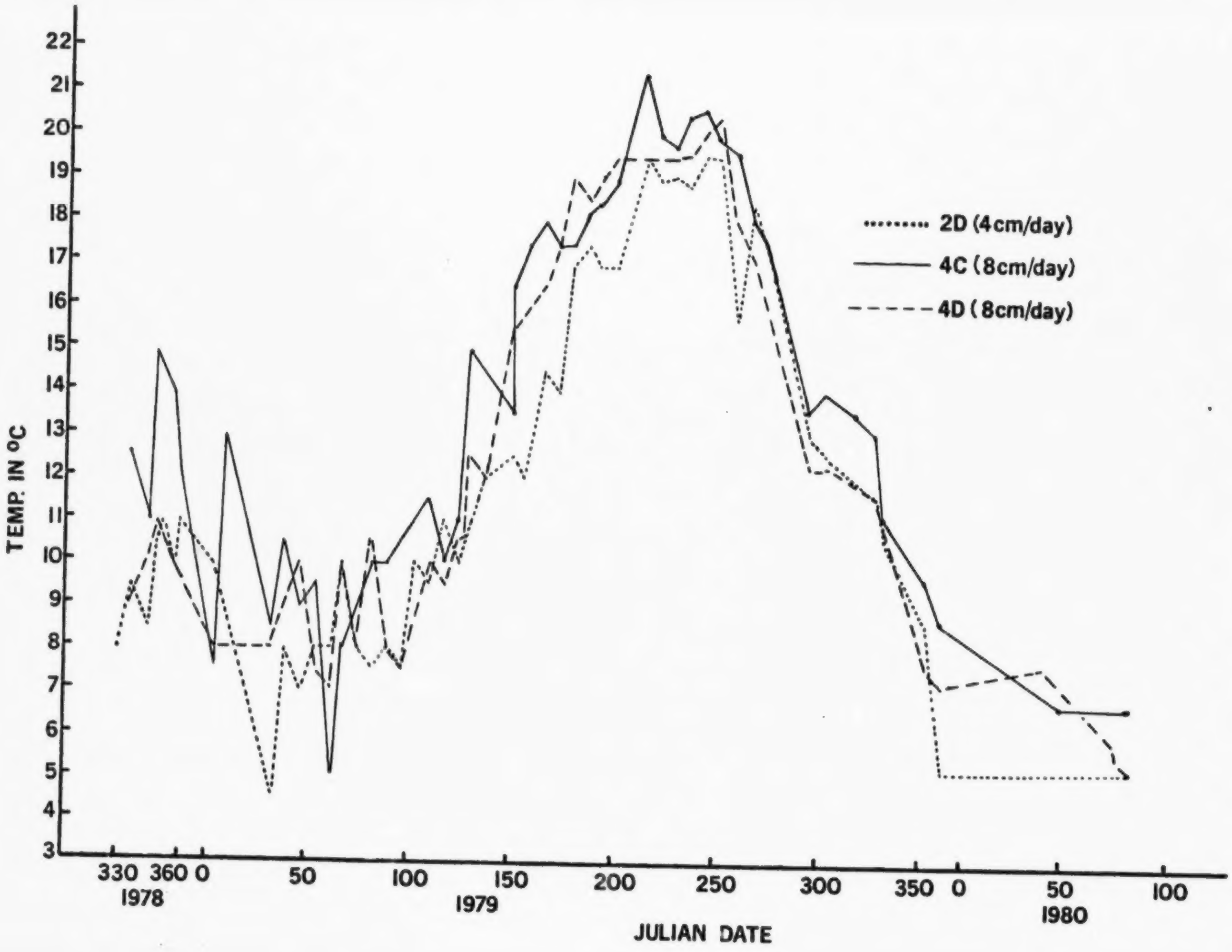


Figure 6-45. Soil temperatures over time for three different rates - Site 1.

SECTION 7

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GLOSSARY

A horizon: An horizon formed at or near the surface, but within the mineral soil, having properties that reflect the influence of accumulating organic matter or eluviation, alone or in combination.

AB horizon: A transitional horizon between the A and B horizons, having features of the A horizon in its upper part and features of the B horizon in its lower part, but without a distinct boundary between the two sets of features.

absorption: The process by which one substance is taken into and included within another substance, as the absorption of water by soil or nutrients by plants.

adsorption: The increased concentration of molecules or ions at a surface, including exchangeable cations and anions on soil particles.

aeration: The effectuation of intimate contact between air and a liquid either by spraying liquid into the air, or by agitating liquid to absorb air.

aerobic: (1) Having molecular oxygen as a part of the environment. (2) Growing or occurring only in the presence of molecular oxygen, as aerobic organisms.

aerobic bacteria: Bacteria that require free elemental oxygen for their growth.

aggregate soil: A group of soil particles that behaves mechanically as a unit.

aggregation: The act or process of forming aggregates, or the state of being aggregated.

air-dry: The state of dryness of a soil that is at equilibrium with the moisture in the surrounding atmosphere.

Alfisol: An order of soils having a B2 horizon high in crystalline clay and a moderately high level of exchangeable bases. These soils usually occur in the climatic range associated with scrub to welldeveloped deciduous forests.

alternative disposal: Any disposal method other than conventional subsurface soil disposal.

alternative treatment: Any treatment method other than conventional septic tank treatment.

ammonification: The biochemical process whereby ammoniacal nitrogen is released from nitrogen-containing organic compounds.

anaerobic: (1) The absence of molecular oxygen.
(2) Growing in the absence of molecular oxygen (such as anaerobic bacteria).

anaerobic bacteria: Bacteria that grow only in the absence of free elemental oxygen.

anaerobic digestion: The degradation of organic matter by microorganisms, in the absence of element oxygen.

anaerobic respiration: The metabolic process by which electrons are transferred from a compound to an inorganic acceptor molecule other than oxygen. The most common acceptor molecules are carbonate, sulfate, and nitrate.

B horizon: An horizon beneath the A horizon, characterized either by its higher colloid (clay or humus) content, or by a color darker or brighter than the soil immediately above or below. (The color is usually associated with colloidal materials). The colloids may have been derived from a texturally-layered parent material; or formed in place, as with clays, including sesquioxides; or, may be illuvial in origin, as with clay and humus.

bacteria: Primitive plants, generally free of pigment, which reproduce by divided along one, two or three planes. They occur as single cells, groups, chains or filaments, and do not require light for their life processes. They may be grown outside of their native habitat with special culturing.

aerobic: Bacteria which require free (elementary) oxygen for their growth.

anaerobic: Bacteria which grow in the absence of free oxygen and breakdown complex substances to derive oxygen.

bar: A unit of pressure equal to one million dynes per square centimeter, which is nearly equal to the standard atmosphere.

base-saturation percentage: The extent to which the adsorption complex of a soil is saturated with exchangeable cations other than hydrogen or aluminum. It is expressed as a percentage of the total cation exchange capacity.

bedrock: The solid rock underlying soils and the regolith at depths ranging from zero (where exposed by erosion) to several hundred feet.

biochemical oxygen demand (BOD): The amount of oxygen required to maintain aerobic conditions during decomposition.

biomass: The total mass of living organisms in a given volume (for example, in seawater, the total mass of living organisms per liter), the total weight of all organisms in any particular environment.

black water: Liquid and solid human body waste and the carriage waters generated through toilet usage.

bulk density, soil: The mass of dry soil per unit bulk volume. The bulk volume is determined before drying to constant weight at 105°C.

C horizon: An horizon of unaltered or slightly altered parent material that normally lies beneath the B horizon, but may lie beneath the A horizon if the only significant soil development process is an increase of organic matter to produce an A horizon.

calcareous soil: Soil containing sufficient calcium carbonate (often with magnesium carbonate) to effervesce visibly when treated with cold 0.1N hydrochloric acid.

capillary attraction: A liquid's movement over or retention by a solid surface due to the interaction of adhesive and cohesive forces.

capillary fringe: A zone just above the water table that is maintained in an essentially saturated state by capillary forces of lift.

cation exchange: The interchange between a cation in solution and another cation on the surface of any surface-active material such as clay or organic colloids.

cation exchange capacity: The sum total of exchangeable cations that a soil can adsorb. Sometimes called total exchange capacity, base exchange capacity, or cation adsorption capacity. Expressed in milliequivalents per 100 grams or per gram of soil (or of other exchanges such as clay).

chemical oxygen demand (COD): A measure of the oxygen equivalent of that portion of organic matter that is susceptible to oxidization by a strong chemical oxidizing agent.

clay: (1) A soil separate consisting of particles 0.002 mm in equivalent diameter. (2) A textural class.

clay mineral: (1) Naturally occurring inorganic crystalline or amorphous material in soils and other earthy deposits, with particles predominantly 0.002 mm in diameter. Largely of secondary origin.

cleavage: Tendency to break in the same direction, thus yielding fragments of predictable shape.

clod: An artificially produced, compact, coherent mass of soil ranging in size from 5 or 10 mm to as much as 8 or 10 inches.

columnar structure: A soil structural type with a vertical axis much longer than the horizontal axes and a distinctly rounded upper surface. See prismatic structure.

coarse texture: The texture exhibited by sands, loamy sands, and sandy loams (except for very fine sandy loam).

coliform-group bacteria: A group of bacteria predominantly inhabiting the intestines of man or animal, but also occasionally found elsewhere. It includes all aerobic and facultative anaerobic, Gram-negative, non-spore-forming bacilli that ferment lactose with production of gas. Also included are all bacteria that produce a dark, purplish-green colony with metallic sheen by the membrane-filter technique used for coliform identification. The two groups are not always identical, but they are generally of similar sanitary significance.

colloids: The finely-divided suspended matter that will not settle, and the apparently dissolved matter that may be transformed into suspended matter by contact with solid surfaces or precipitation by chemical treatment. Substances which are soluble as judged by ordinary physical tests, but will not pass through a parchment membrane.

compaction: The reduction of soil porosity, accomplished by forcing soil particles into a closer configuration.

compressive forces: Forces that squeeze a soil mass and reduce overall porosity.

concentration: The relative content of a substance. Example: The strength of a solution.

conductivity, hydraulic: As applied to soils -- the ability of the soil to transmit water in liquid form through pores.

consistence: (1) The resistance of a material to deformation or rupture. (2) The degree of cohesion or adhesion of the soil mass. Terms used for describing consistence at various soil moisture contents are:

wet soil: Nonsticky, slightly sticky, sticky, very sticky, nonplastic, slightly plastic, plastic, and very plastic.

moist soil: Loose, very friable, friable, firm, very firm, and extremely firm.

dry soil: Loose, soft, slightly hard, hard, very hard, and extremely hard.

cementation: Weakly cemented, strongly cemented, and indurated.

crumb: A soft, porous, more or less rounded ped from 1 to 5 mm in diameter.

crust: A surface layer on soils, ranging in thickness from a few millimeters to perhaps as much as an inch, that is much more compact, hard, and brittle, when dry, than the material immediately beneath it.

degradation: The breakdown of substances by biological action.

denitrification: The biochemical reduction of nitrate or nitrite to gaseous molecular nitrogen or an oxide of nitrogen.

digestion: (1) The biological decomposition of organic matter in sludge, resulting in partial gasification, liquefaction and mineralization. (2) The process carried out in a digester.

dissolved oxygen: The oxygen dissolved in water, wastewater or other liquid, usually expressed in milligrams per liter (mg/L), parts per million (ppm) or percent of saturation. Abbreviated DO.

double layer: In colloid chemistry, a double layer of electrical charges, one consisting of the charges provided by the solid phase (usually negative) and the second by absorbed ions of opposite charge.

E. coli: Abbreviation of Escherichia coli.

effluent: Sewage and water or another liquid; untreated, partially or completely treated; and flowing out of a reservoir, basin, treatment plant or a part thereof.

eluviation: The removal of soil material in suspension from a layer or layers of a soil. (Usually, the loss of material in solution is described by the term leaching).

Escherichia coli (E. coli): One of the species of bacteria in the coliform group. Its presence is considered indicative of fresh fecal contamination.

facultative anaerobic bacteria: Bacteria that can adapt to growth in either the presence or absence of oxygen. May be referred to as facultative bacteria.

field capacity: The water that remains in a field soil that has been thoroughly wetted and drained until free drainage has practically ceased.

filtering medium: Any material through which water, wastewater or other liquid is passed for the purpose of purification, treatment or conditioning.

filter clogging: The effect occurring either when fine particles fill the voids of a sand filter or biological bed; or,when growths form surface mats that retard the normal passage of liquid through the filter.

filtrate: The liquid that has passed through a filter.

fine texture: The texture exhibited by soils having clay as part of their textural class name.

five-day BOD: That part of oxygen demand associated with biochemical oxidation of carbonaceous, as distinct from nitrogeneous, material. It is determined by allowing biochemical oxidation to proceed, under conditions specified in Standard Methods, for five days.

gravitational potential: See potential, soil water.

greywater: Liquid and solid wastes generated by water - using fixtures and appliances excluding the toilet and possibly the garbage disposal.

groundwater: That portion of the total precipitation that at any particular time is either passing through or standing in the soil and the underlying strata, and is free to move under the influence of gravity.

head: The energy, either kinetic or potential, possessed by each unit weight of a liquid, expressed as the vertical height through which a unit weight would have to fall to release the average energy possessed. It is used in various compound terms such as pressure head, velocity head and loss of head.

heavy soil: (Obsolete in scientific use). A soil with a high content of the fine separates, particularly clay, or one with a high drawbar pull and hence difficult to cultivate. See fine texture.

hydraulic conductivity: See conductivity, hydraulic.

hydraulic gradient: The slope of the hydraulic grade line; the rate of change of pressure head; the ratio of the loss in the sum of the pressure head and a position head to the flow distance. For open channels, it is the slope of the water surface and is frequently considered parallel to the invert. For closed conduits under pressure, it is the slope of the line joining the elevations to which water would rise in pipes freely vented and under atmospheric pressure. A positive slope is usually one that drops in the direction of flow.

hydrolysis: The chemical reaction of a compound with water, in which the anion from the compound combines with the nitrogen and the cation from the compound combines with the hydroxyl from the water to form an acid and a base.

illuviation: The process of deposition of colloidal soil material, removed from one horizon to another in the soil; usually from an upper to a lower horizon in the soil profile. See eluviation.

impervious: Resistant to penetration by fluids or by roots.

infiltration: The downward entry of water into the soil.

influent: Water, wastewater or other liquid flowing into a reservoir, basin or treatment plant or any unit thereof.

inorganic matter: Chemical substances of mineral origin, or more correctly, not of basically carbon structure.

ion exchange: A chemical process involving reversible interchange of ions between a liquid and a solid but no radical change in structure of the solid.

leach: To cause water or other liquid to percolate through a substance.

leaching: The removal of materials in solution from the soil.

liquefaction: Act or process of liquefying or of rendering or becoming liquid; reduction to a liquid state.

liquor: Water, wastewater, or any combination; commonly used to designate liquid phase when other phases are present.

loess: Material transported and deposited by wind and consisting of predominantly silt-sized particles.

lysimeter: A device for measuring percolation and leaching losses from a column of soil under controlled conditions.

manometer: An instrument for measuring pressure. Usually a U-shaped tube containing a liquid; the liquid surface in one end of the tube moves proportionally with changes in pressure on the liquid in the other end. Also, a tube type of differential pressure gage.

mapping unit: A soil or combination of soils delineated on a map and, where possible, named to show the taxonomic unit or units included. Principally, mapping units on maps of soils depict soil types, phases, associations, or complexes.

matric potential: See potential, soil water.

medium texture: The texture exhibited by very fine sandy loams, loams, silt loams, and silts.

milligrams per liter: A unit of the concentration of water or wastewater constituent. It is 0.001 g of the constituent in 1,000 ml of water. It has replaced the unit formerly used commonly, parts per million, to which it is approximately equivalent, in reporting the results of water and wastewater analysis.

mineral: Any of a class of substances occurring in nature, usually comprising inorganic substances, such as quartz and feldspar, of definite chemical composition and usually of definite crystal structure, but sometimes also including rocks formed by these substances as well as certain natural products of organic origin, such as asphalt and coal.

mineralization: The conversion of an element from an organic form to an inorganic state as a result of microbial decomposition.

mineral soil: A soil consisting predominantly of, and having its properties determined by, mineral matter. Usually contains 20% organic matter, but may contain an organic surface layer up to 30 cm thick.

Mollisol: Soil order consisting of soils having a thick A horizon with more than one percent organic matter and a base-saturation percentage above 50. Normally, they are formed under grass vegetation. Distinguished from Vertisols in that they are not self-inverting.

montmorillonite: An aluminosilicate clay mineral with a 2:1 expanding structure; that is, with two silicon tetrahedral layers enclosing an aluminum octahedral layer. Considerable expansion may be caused by water moving between silica layers of contiguous units.

morphology: See soil morphology.

mottling: Spots or blotches of different color or shades of color interspersed with the dominant color.

nitrification: The biochemical oxidation of ammonium to nitrate.

optimum moisture content for compaction: The moisture content at Which a soil achieves maximum density upon compaction. Each combination of soil and compactive effort has a unique optimum moisture content for compaction.

organic matter: Chemical substances of animal or vegetable origin, or more correctly, of basically carbon structure, comprising compounds consisting of hydrocarbons and their derivatives.

organic soil: A soil which contains a high percentage (15% or 20%) of organic matter throughout the solum.

osmotic potential: See potential, soil water.

osmotic pressure: In concept, the force per unit area required to equal the attractive (hydration) force for water exerted by ions dissolved in a solution.

oven-dry soil: Soil which has been dried at 105°C until it reaches an essentially constant weight.

oxidation-reduction potential: The potential required to transfer electrons from the oxidant to the reductant and used as a qualitative measure of the state of oxidation in wastewater treatment systems.

oxygen demand: The quantity of oxygen utilized in the biochemical oxidation of organic matter in a specified time, at a specified temperature and under specified conditions. See BOD.

parent material: The unconsolidated mineral or organic matter from which soils are developed.

particle density: The mass per unit volume of individual particles; usually expressed as grams per cubic centimeter.

particle size: The effective diameter of a particle usually measured by sedimentation or sieving.

particle-size distribution: The amounts of the various soil separates in a soil sample, usually expressed as weight percentages.

ped: A unit of soil structure such as an aggregate, crumb, prism, block, or granule, formed by natural processes (in contrast with a clod, which is formed artificially).

pedon: The smallest volume (soil body) which displays the normal range of variation in properties of a soil. Where properties such as horizon thickness vary little along a lateral dimension, the pedon may occupy an area of a square yard or less. Where such a property varies substantially along a lateral dimension, a large pedon several square yards in area may be required to show the full range in variation.

percolation: The flow or trickling of a liquid downward through a contact or filtering medium. The liquid may or may not fill the pores of the medium.

percolation, soil water: The downward movement of excess water through soil.

permeability,soil: The ease with which gases, liquids, or plant roots penetrate or pass through soil.

pH: A measure of acidity and alkalinity, neutrality being at pH 7; pH under 7 indicates an acid solution and pH over 7 an alkaline solution; the nearer the pH to 7 the weaker the acid or alkali. The reciprocal of the logarithm of the hydrogen ion concentration. The concentration is the weight of hydrogen ions, in grams, per liter of solution. Neutral water, for example, has a pH value of 7 and a hydrogen ion concentration of 10^{-7}.

phosphate: A salt or ester of phosphorus acid.

plastic soil: A soil capable of being molded or deformed continuously and permanently, by relatively moderate pressure, into various shapes. See consistence.

platy structure: Soil aggregates that are developed predominantly along the horizontal axes; laminated; flaky.

plow pan: A compacted layer beneath the plowlayer produced by pressure exerted on the soil during plowing.

potential, soil water: The potential energy of a unit quantity of water reduced by the interaction of the water with such forces as capillary (matric), ion hydration (osmotic), and gravity, expressed relative to an arbitrarily selected reference potential. In practical application, potentials are used to predict the direction and rate of water flow through soils, or between the soil and some other system, such as plants or the outer atmosphere. Flow occurs spontaneously between points of different water potential, the direction of flow being toward the site of lower potential.

pore-size distribution: The volume of the various size of pores in a soil. Expressed as percentages of the bulk volume (soil plus pore space).

pore space: Space in the soil not occupied by solid particles.

Porosity: The total volume of pore space; usually expressed as a percentage of the total soil volume.

prismatic structure: A soil structural type with a vertical axis much longer than the horizontal axes and a flat or indistinct upper surface. See columnar structure.

profile, soil: A vertical section of the soil through all its horizons and extending into the parent material.

puddled soil: A soil in which structure has been mechanically destroyed, which allows the soil to run together when saturated with water. A soil that has been puddled occurs in a massive nonstructural state.

raw wastewater: Wastewater before it receives any treatment.

sand: (1) A soil separate consisting of particles between 0.05 and 2.0 mm in diameter. (2) A soil textural class.

saturate: (1) To fill all the voids between soil particles with a liquid.
(2) To form the most concentrated solution possible under a given set of physical conditions in the presence of an excess of the solute.
(3) To fill to capacity, as the adsorption complex with a cation species; e.g., H-saturated, etc.

saturation: A condition reached by a material, whether it be in solid, gaseous or liquid state, that holds another material within itself in a given state in an amount such that no more of such material can be held within it in the same state. The material is then said to be saturated or in a condition of saturation.

separate: See soil separates.

settleable solids: That matter in wastewater which will not stay in suspension during a preselected settling period, such as one hour, but either settles to the bottom or floats to the top.

shearing forces: Forces which cause one soil mass to move relative to another, typically producing a layer of soil with many particles oriented parallel to the imposed force.

silt: (1) A soil separate consisting of particles between 0.05 and 0.002 mm in diameter. (2) A soil textural class.

single-grained state: A nonstructural state normally observed in soils containing a preponderance of large particles such as sand. Because of a lack of cohesion, the sand grains tend not to assemble in aggregate form.

soil: (1) The unconsolidated mineral material on the immediate surface of the earth that serves as a natural medium for the growth of land plants. (2) The unconsolidated mineral matter on the surface of the earth that has been subjected to and influenced by genetic and environmental factors of parent material, climate (including moisture and temperature), macro- and microorganisms, and topography, all acting over a period of time and producing a product-soil that differs from the material from which it is derived in many physical, chemical, biological, and morphological properties.

soil classification: The systematic arrangement of soils into groups or categories on the basis of their characteristics. Broad groupings are made on the basis of general characteristics and subdivisions on the basis of more detailed differences in specific properties. The three higher categories, which are broadly defined, are orders, suborders, and great groups. The lowest category is the soil series, with each series consisting of many individual occurrences or bodies of soil that are very similar in.most respects.

soil genesis: The formation of soils; the creation of new characteristics by soil-development processes.

soil horizon: A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics such as color, structure, texture, consistence, or pH.

soil morphology: The physical constitution, particularly the structural properties, of a soil profile as exhibited by the kinds, thickness, and arrangement of the horizons in the profile, and by the texture, structure, consistence, and porosity of each horizon.

soil map: A map showing the distribution of soil types or other soil mapping units in relation to the prominent physical and cultural features of the earth's surface.

soil moisture: Water contained in the soil.

soil separates: Groups of mineral particles separated on the basis of a range in size. The principal separates are sand, silt, and clay.

soil series: The basic unit of soil classification and consisting of soils which are essentially alike in all major profile characteristics although the texture of the A horizon may vary somewhat. See soil type.

soil solution: The aqueous liquid phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials.

soil structure: The combination or arrangement of individual soil particles into definable aggregates, or peds, which are characterized and classified on the basis of size, shape, and degree of distinctness.

soil suction: A measure of the force of water retention in unsaturated soil. Soil suction is equal to a force per unit area that must be exceeded by an externally applied suction to initiate water flow from the soil. Soil suction is expressed in standard pressure terms.

soil survey: The systematic examination, description, classification, and mapping of soils in an area.

soil texture: The relative proportions of the various soil separates in a soil.

soil type: In mapping soils, a subdivision of a soil series based on differences in the texture of the A horizon.

soil water: A general term emphasizing the physical rather than the chemical properties and behavior of the soil solution.

solids: Material in the solid state.

total: The solids in water, sewage or other liquids; includes suspended and dissolved solids; all material remaining as residue after water has been evaporated.

dissolved: Solids which are present in solution.

suspended: Solids which are physically suspended in water, sewage or other liquids. The quantity of material deposited when a quantity of water, sewage, or other liquid is filtered through an asbestos mat in a Gootch crucible.

volatile: The quantity of solids in water, sewage or other liquid lost on ignition of total solids.

solum (plural: sola): The upper and most weathered part of the soil profile; the A and B horizon.

structure, soil: See soil structure.

subsoil: In general concept, that part of the soil below the depth of plowing.

substrate: The substance on which an enzyme acts to form the product.

suction: See soil suction.

surface soil: The uppermost part of the soil, ordinarily moved in tillage, or its equivalent in uncultivated soils and ranging in depth from 3 to 4 inches to 8 to 10 inches. Frequently designated as the plow layer or the Ap horizon.

tensiometer: A device for measuring the negative hydraulic pressure (or tension) of water in soil in situ; a porous, permeable ceramic cup connected through a tube to a manometer or vacuum gauge.

tension, soil water: The expression, in positive terms, of the negative hydraulic pressure of soil water.

texture: See soil texture.

textural class, soil: Soils groups on the basis of a specified range in texture. In the United States 12 textural classes are recognized.

tight soil: A compact, relatively impervious and tenacious soil (or subsoil) which may or may not be plastic.

till: (1) Unstratified glacial drift deposited directly by the ice and consisting of clay, sand, gravel, and boulders intermingled in any proportion. (2) To plow and prepare for seeding; to seed or cultivate the soil.

topsoil: (1) The layer of soil moved in cultivation. See surface soil: (2) The A horizon. (3) The A1 horizon. (4) Presumably fertile soil material used to topdress roadbanks, gardens, and lawns.

unsaturated flow: The movement of water in a soil that is not filled to capacity with water.

water content: As applied to soils work - the amount of water held in a soil expressed on a weight or volume basis. Conventionally, water contents are expressed relative to the oven-dry weight or volume of soil.

water table: That level in saturated soil where the hydraulic pressure is zero.

water table, perched: The water table of a discontinuous saturated zone in a soil.